

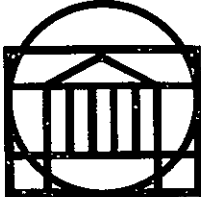
(NASA-CR-156122) UNSTEADY LOADS DUE TO
PROPULSIVE LIFT CONFIGURATIONS. PART C:
DEVELOPMENT OF EXPERIMENTAL TECHNIQUES FOR
INVESTIGATION OF UNSTEADY PRESSURES BEHIND A
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RESEARCH LABORATORIES FOR THE ENGINEERING SCIENCES



SCHOOL OF ENGINEERING AND APPLIED SCIENCE

University of Virginia
Charlottesville, Virginia 22901

Technical Report

UNSTEADY LOADS DUE TO PROPULSIVE LIFT CONFIGURATIONS
PART C - DEVELOPMENT OF EXPERIMENTAL TECHNIQUES FOR
INVESTIGATION OF UNSTEADY PRESSURES BEHIND A COLD MODEL JET

Submitted to:

NASA Scientific and Technical Information Facility
P. O. Box 8757
Baltimore/Washington International Airport
Maryland 21240

Submitted by:

J. K. Haviland
Professor

James C. Schroeder



Report No. UVA/528095/MAE78/113

March 1978

RESEARCH LABORATORIES FOR THE ENGINEERING SCIENCES

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Technical Report

UNSTEADY LOADS DUE TO PROPULSIVE LIFT CONFIGURATIONS
PART C - DEVELOPMENT OF EXPERIMENTAL TECHNIQUES FOR
INVESTIGATION OF UNSTEADY PRESSURES BEHIND A COLD METAL JET

Submitted to:

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ABSTRACT

As part of an overall study of the scaling laws for the fluctuating pressures induced on the wings and flaps of STOL aircraft by jet engine impingement, an experimental investigation has been made of the near field fluctuating pressures behind a cold circular jet, both when it was free and when it was impinging on a flat plate. Minature static pressure probes were developed for measurements in the free jet and on the flat plate; these were connected by plastic tubing to 1/8 inch microphones which acted as pressure transducers. Using a digital correlator together with an FFT program on the CDC 6400 computer, spectral densities, relative amplitudes, phase lags, and coherences were also obtained for the signals from pairs of these probes, and were used to calibrate these probes directly against microphones. This system of instrumentation was employed to obtain single point rms and third-octave surveys of the static pressures in the free jet and on the surface of the plate. Also, two point cross-correlations were obtained, and from these, relative amplitudes, phase lags, and coherences were calculated for a more detailed characterization of the jet flow. These measurements confirmed the existence of a vortex structure in the jet, and demonstrated that the jet diameter, velocity and dynamic pressure are appropriate scaling dimensions for characterizing fluctuating pressures behind jets.

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TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iii
ABSTRACT	iv
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF SYMBOLS	xiii
Chapter	
1. INTRODUCTION	1
2. HISTORICAL AND THEORETICAL BACKGROUND	4
2.0 Classical Model of a Circular Jet	4
2.1 Vortex Model of a Circular Jet	6
2.2 Scaling Laws for a Circular Jet	13
2.3 Jet Impingement	14
3. INSTRUMENTATION AND DATA ANALYSIS TECHNIQUES FOR PRESSURE MEASUREMENTS	17
3.0 Flow and Traverse System	17
3.1 Pressure Sensors	18
3.2 Data Analysis Equipment	24
3.3 Fast Fourier Transform Analysis	26
4. EVALUATION OF DATA ANALYSIS TECHNIQUES AND PRESSURE SENSORS	32
4.0 Evaluation of Data Analysis Techniques	32
4.1 Theoretical Pressure Sensor Transfer Functions	38
4.2 Evaluation of Pressure Sensors	48
4.3 Calculated Transfer Functions	58

TABLE OF CONTENTS (continued)

Chapter		<u>Page</u>
5.	EXPERIMENTAL RESULTS	65
5.0	Free Jet - P_{rms} and Mean Dynamic Pressure Levels	65
5.1	Free Jet - 1/3 Octave Spectra	69
5.2	Free Jet - Correlation Coefficients	77
5.3	Free Jet - Phase lag, Transfer Function Amplitude and Coherence	80
5.4	Jet Impingement - Fluctuating Pressure Levels . .	87
5.5	Jet Impingement - 1/3 Octave Spectra	88
5.6	Jet Impingement - Correlation Coefficients	103
5.7	Jet Impingement - Phase Lag, Transfer Function Amplitude and Coherence	109
6.	SUMMARY	131
	BIBLIOGRAPHY	134

LIST OF TABLES

Table		<u>Page</u>
1	Probe Correlation Coefficient Comparison	49
2	Free Jet - Convection Velocities	87
3	Jet Impingement - Convection Velocities	130

ORIGINAL PAGE IS
OF POOR QUALITY

LIST OF FIGURES

Figure	<u>Page</u>
2.0.1 Classical Model of a Circular Jet	5
2.1.1 Vortex Model of a Circular Jet	7
2.1.2 a) Vortex Sheet Roll Up	9
2.1.2 b) Lobed Vortex Ring	9
2.1.3 Limits of Sheared Annulus	11
2.1.4 Vortex Model Fluctuations	12
3.0.1 Cold Jet Assembly	19
3.0.2 Data Acquisition Set-Up	20
3.1.1 Pressure Probes	22
3.1.2 Flat Impingement Plate	23
3.3.1 CROSSPECT Model	27
4.0.1 Power Spectra from 9.0 cm Downstream Location	33
4.0.2 Power Spectra from 11.0 cm Downstream Location	34
4.0.3 Transfer Function Amplitude Output	35
4.0.4 Phase Lag and Coherence Outputs	36
4.0.5 Power Spectra from Normal Dynamic Range	37
4.0.6 Power Spectra from Extended Dynamic Range	37
4.0.7 Power Spectra Output from CROSSPECT	39
4.0.8 1/3 Octave Spectra	39
4.0.9 Comparison Between Power Spectra and 1/3 Octave	40
4.1.1 Model for Analysis of Pressure Probes	42
4.1.2 Pulsating Air Slug	44
4.1.3 Pulsating Sphere	44

LIST OF FIGURES (continued)

Figure	Page
4.1.4 Equivalent Piston	46
4.1.5 Equivalent Pulsating Sphere	46
4.2.1 1/3 Octave Spectra: Total and Static	50
4.2.2 Power Spectra: Static	51
4.2.3 Power Spectra: Total	51
4.2.4 Transfer Function of Static Probe	53
4.2.5 Transfer Function of New Static Probe	53
4.2.6 Special Impingement plate	55
4.2.7 Transfer Function: Tubing Length = 0.5 m	56
4.2.8 Transfer Function: Tubing Length = 1.0 m	56
4.2.9 Transfer Function: Tubing Length = 2.0 m	56
4.2.10 Transfer Function: Diameter = .01 m	57
4.2.11 Transfer Function: Diameter = .02 m	57
4.2.12 Transfer Function: Diameter = .04 m	57
4.2.13 Comparison Between Microphone and Kulite	59
4.2.14 Comparison Between Stainless and Plastic Tubing	59
4.3.1 Calculated Transfer Function Amplitude and Phase Lag for Static Pressure Probe	61
4.3.2 Compensated Spectral Density for Probe	62
4.3.3 Compensated Phase Lag and Transfer Function Amplitude for Probe	62
4.3.4 Calculated Transfer Function Amplitude and Phase Lag for Pressure Port	63
4.3.5 Compensated Spectral Density for Port	64

LIST OF FIGURES (continued)

Figure	Page
4.3.6 Compensated Phase Lag and Transfer Function Amplitude for Port	64
5.0.1 Definition of Coordinate Systems	66
5.0.2 Free Jet Fluctuating Pressure Level Profiles	67
5.0.3 Free Jet Mean Dynamic Pressure Profiles	68
5.1.1 Free Jet 1/3 Octave Spectra: X/D=2	70
5.1.2 Free Jet 1/3 Octave Spectra: X/D=3	71
5.1.3 Free Jet 1/3 Octave Spectra: X/D=4	72
5.1.4 Free Jet 1/3 Octave Spectra: X/D=5	73
5.1.5 Free Jet 1/3 Octave Spectra: X/D=6	74
5.1.6 Free Jet 1/3 Octave Spectra: X/D=8	75
5.1.7 Free Jet 1/3 Octave Spectra: X/D=10	76
5.2.1 Free Jet Correlation Coefficients: X/D=2-5	78
5.2.2 Free Jet Correlation Coefficients: X/D=6, 8, 10	79
5.3.1 Free Jet Phase Lag, Transfer Function Amplitude and Coherence: X/D=2; Y/D=0.142, 0.25	81
5.3.2 Free Jet Phase Lag, Transfer Function Amplitude and Coherence: X/D=2; Y/D=0.50, 0.75	82
5.3.3 Free Jet Phase Lag, Transfer Function Amplitude and Coherence: X/D=4, 10; Y/D=0.50	83
5.3.4 Free Jet Phase Lag, Transfer Function Amplitude and Coherence: Probe Separation=1.0 cm; X/D=1, 2	85
5.3.5 Free Jet Phase Lag, Transfer Function Amplitude and Coherence: Probe Separation=1.0 cm; X/D=4, 10	86
5.4.1 Jet Impingement Fluctuating Pressure Levels: $\beta=0^\circ$	89

LIST OF FIGURES (continued)

Figure	Page
5.4.2 Jet Impingement Fluctuating Pressure Levels: $\beta = 30^\circ$. .	90
5.4.3 Jet Impingement Fluctuating Pressure Levels: $\beta = 60^\circ$. .	91
5.4.4 Jet Impingement Fluctuating Pressure Levels: $\beta = 90^\circ$. .	92
5.5.1 Jet Impingement 1/3 Octave Spectra: $X/D=2, 4, 6$; $\beta = 0^\circ$.	94
5.5.2 Jet Impingement 1/3 Octave Spectra: $X/D=2$; $\beta = 30^\circ$. . .	95
5.5.3 Jet Impingement 1/3 Octave Spectra: $X/D=4$; $\beta = 30^\circ$. . .	96
5.5.4 Jet Impingement 1/3 Octave Spectra: $X/D=6$; $\beta = 30^\circ$. . .	97
5.5.5 Jet Impingement 1/3 Octave Spectra: $X/D=2$; $\beta = 60^\circ$. . .	98
5.5.6 Jet Impingement 1/3 Octave Spectra: $X/D=4$; $\beta = 60^\circ$. . .	99
5.5.7 Jet Impingement 1/3 Octave Spectra: $X/D=6$; $\beta = 60^\circ$. . .	100
5.5.8 Jet Impingement 1/3 Octave Spectra: $X/D=4$; $\beta = 90^\circ$. . .	101
5.5.9 Jet Impingement 1/3 Octave Spectra: $X/D=6$; $\beta = 90^\circ$. . .	102
5.6.1 Jet Impingement Correlation Coefficients: $\beta = 0^\circ$	104
5.6.2 Jet Impingement Correlation Coefficients: $\beta = 30^\circ$	105
5.6.3 Jet Impingement Correlation Coefficients: $\beta = 30^\circ$	106
5.6.4 Jet Impingement Correlation Coefficients: $\beta = 60^\circ$	107
5.6.5 Jet Impingement Correlation Coefficients: $\beta = 90^\circ$	108
5.7.1 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence: $\beta = 0^\circ$; $X/D=2, 4$; $\eta/D=1.0$	110
5.7.2 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence: $\beta = 0^\circ$; $X/D=6$; $\eta/D=1.0$	111
5.7.3 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence: $\beta = 30^\circ$; $X/D=2$; $\eta/D=1.5, 0.25$	112
5.7.4 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence: $\beta = 30^\circ$; $X/D=2$; $\eta/D=-0.25, -1.5$	113

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LIST OF FIGURES (continued)

Figure	Page
5.7.5 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence: $\beta=30^\circ$; $X/D=2$; $\xi/D=0.25, 1.5$	114
5.7.6 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence: $\beta=30^\circ$; $X/D=4$; $\eta/D=1.0, -1.0$	115
5.7.7 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=30^\circ$; $X/D=4$; $\xi/D=1.0$	116
5.7.8 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=30^\circ$; $X/D=6$; $\eta/D=1.0, -1.0$	117
5.7.9 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=30^\circ$; $X/D=6$; $\xi/D=1.0$	118
5.7.10 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=60^\circ$; $X/D=2$; $\eta/D=1.0, -1.0$	119
5.7.11 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=60^\circ$; $X/D=2$; $\xi/D=1.0$	120
5.7.12 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=60^\circ$; $X/D=4$; $\eta/D=1.0, -1.0$	121
5.7.13 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=60^\circ$; $X/D=4$; $\xi/D=1.0$	122
5.7.14 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=60^\circ$; $X/D=6$; $\eta/D=1.0, -1.0$	123
5.7.15 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=60^\circ$; $X/D=6$; $\xi/D=1.0$	124
5.7.16 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=90^\circ$; $X/D=4$; $\eta/D=1.0, -1.0$	125
5.7.17 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=90^\circ$; $X/D=4$; $\xi/D=1.0$	126
5.7.18 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=90^\circ$; $X/D=6$; $\eta/D=1.0, -1.0$	127
5.7.19 Jet Impingement Phase Lag Transfer Function Amplitude and Coherence: $\beta=90^\circ$; $X/D=6$; $\xi/D=1.0$	128

LIST OF SYMBOLS

a	Total Area of pressure sensing holes
A	Cross sectional area of tubing system
C	Speed of sound
d	Diameter of pressure sensing hole
d	Effective diameter of group of pressure sensing holes
D	Diameter of Jet
f	Frequency
G_{AA}	Power Spectral density
G_{AB}	Cross Spectral density
k	Wave Number
L	Tubing length
l	length of pressure sensing hole
MF	Multiplication Factor
n	Uncorrelated pressure disturbance
N	Number of measurements
U_c	Convection Velocity
U_p	Velocity of pulsating piston
U_s	Velocity of pulsating sphere
X	Downstream distance from Jet exit
X	Volume Flow Rate
Y	Radial distance from centerline of Jet
Z_m	Microphone Impedance
β	Plate impingement angle
η	Streamwise distance from center of flat plate

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LIST OF SYMBOLS (continued)

ξ	Radial distance from center of Flat plate
ρ	Fluid density
ω	Angular frequency
$(\gamma_{12})^2$	Coherence

Chapter 1

INTRODUCTION

STOL (short-take-off and landing) aircraft design has recently become a concept of interest for providing short range aircraft service. These powered lift aircraft configurations make it possible to operate from small runways, which can be located close to heavily populated areas. The in-flight characteristics and performance are virtually the same for these aircraft as for conventional aircraft. However, in the take-off and landing configurations, these aircraft are substantially different from conventional aircraft, indicating the need for both experimental and theoretical investigation.

Two forms of STOL aircraft are of special interest, the externally blown flap [EBF] configuration and the upper-surface-blown [USB] configuration. The EBF configuration consists of large flap, which is placed in the jet, deflecting air downwards. This powered lift concept converts the engine thrust into lift and also gains additional lift due to entrainment of air flow over the wing. The USB configuration, with jet engines mounted over the wings, produce extra lift by maintaining circulation over the wing to a high effective angle of attack.

The pressure loads experienced by these STOL configurations are a result of static pressures and fluctuating or unsteady pressures. The exact nature of these fluctuating pressure loads developed on the flaps is presently unknown. Therefore, prototype aircraft now under construction use flaps that are over-designed to account for uncertainty in the levels of these unsteady loads. Careful structural design of

these flaps is essential to keep the extra weight of additional flaps within economical bounds. This structural design is not possible without accurate information on the loading to which these flaps will be subject. The objectives of this report is toward the accurate predictions of the levels of these unsteady loads and covers the establishment and development of pressure measuring techniques, which are applied to the fluctuating pressures behind a small free cold jet and behind a cold jet impinging on a flat plate. Ultimately, the goal is to establish scaling laws that will make it possible to predict loads on full scale STOL configurations. The important scaling parameters have been found to be q_j [jet exit dynamic pressure], U_j [jet exit velocity], D_j [jet exit diameter]. Three of these combine in the use of Strouhal number [$S_t = D_j f / U_j$]. No large variation of the Mach numbers, M , was possible. Through the use of dimensionless groups of these parameters, the results of experimentation behind a cold jet may be used for predicting levels behind a full scale STOL configuration.

A brief summary of the theoretical and historical background pertinent to the investigation of fluctuating pressures induced on the wings and flaps of STOL aircraft due to jet impingement is initially presented. Miniature pressure probes were developed for measurement of fluctuating pressures in the near field of a cold circular jet, both when it was free, and when it was impinging on a flat plate. In analyzing the fluctuating pressures, considerable use has been made of a digital correlator for the cross correlation of pressure fluctuations at different points. Also, use has been made of a computer program

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which converts the correlations to auto and cross-spectra, and determines phase and coherence values between the pairs. Single point rms and third-octave surveys of the static pressures behind the jet and fluctuating surface pressures on the plate were also made. The data analysis techniques and pressure sensors are described in detail, with evaluation of the data analysis system and investigation of the instrumentation induced transfer functions.

The measurements confirm the existence of a vortex structure in the jet and also on the flat plate. This investigation also demonstrated that the jet diameter, velocity and dynamic pressure are appropriate scaling dimensions for characterizing fluctuating pressure behind jets.

Chapter 2

HISTORICAL AND THEORETICAL BACKGROUND

2.0 Classical Model of a Circular Jet

The classical model of a circular jet is shown in Figure 2.0.1. In this model, the jet is divided into three regions, the initial zone extending from the jet exit to approximately five diameters downstream, the adjustment zone extending from five diameters downstream to between ten and forty diameters, and the fully developed zone which extends beyond the adjustment zone. The initial zone is further sub-divided into the potential core, sheared annulus, and entrainment regions.^[1]

The potential core, conical in shape, which is characterized by low turbulence levels and by a constant mean velocity, diminishes uniformly due to the inward spread of the sheared annulus. The sheared annulus is a region of intense turbulence which totally engulfs the jet flow at the beginning of the adjustment zone. The entire jet is surrounded by the entrainment region which is an area of induced flow.

In this classical model, the interaction between the moving fluid flow and the still air creates turbulence in the sheared annulus, this velocity discontinuity creates broad band turbulent fluctuations or eddy currents. This model gives a broad spectrum of equal energy levels in the initial zone.^[2] In the fully developed zone [self-similar region] both the average velocity and fluctuating velocities decrease, while the lower frequency content of the spectrum increases, with increasing downstream location and region spreading. All quantities, in the fully developed zone, can be non-dimensionalized using downstream distance and jet exit velocity.

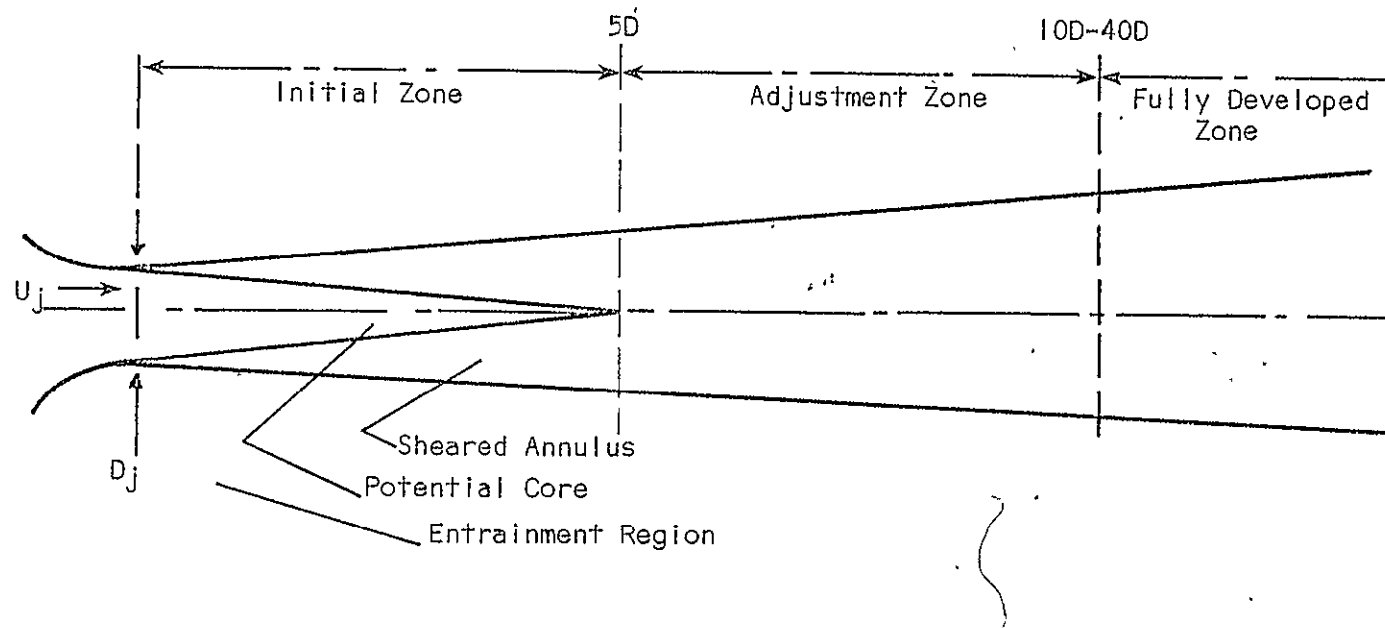


Figure 2.0.1 Classical Model of a Circular Jet

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The classical model fails to explain the following observations made in the initial zone of a jet, using hot wire anemometers and microphones with nose cones.^[4] For this reason, a vortex model of a circular jet has been proposed and is explained in the next section.

Strong dependence on Strouhal number $[D_j f/U_j]$ has been observed in turbulence spectra in the initial zone and in the far field. This indicates that the size of the turbulence eddies is determined by jet diameter, whereas the sheared annulus concept argues for independence from jet diameter. Also, since peaks at Strouhal numbers of between 0.3 and 0.5 are encountered, the eddies must have diameters of the order of the jet diameter, or greater, and must therefore be too large to fit into the annular region unless they are annular themselves.

There have been observations of strong near-field pressure fluctuations in the entrainment region immediately outside the sheared annulus. These are near-field disturbances, not sound waves, that convect along the jet axis at about 60% of the jet exit velocity, with a spacing of about two jet diameters.^[3]

2.1 Vortex Model of a Circular Jet

The vortex model of a circular jet is shown in Figure 2.1.1. In this model the annular vortex tube formed by the jet breaks up into individual vortex rings, these travel at a convection velocity, U_c , which is near half of the jet velocity, U_j .^[5] Such a model was studied in detail by Crow and Champagne,^[6] who also found that these vortex rings are spaced on the average of about two jet diameters, D_j , giving rise to a spectral peak at Strouhal number of about 0.3 where

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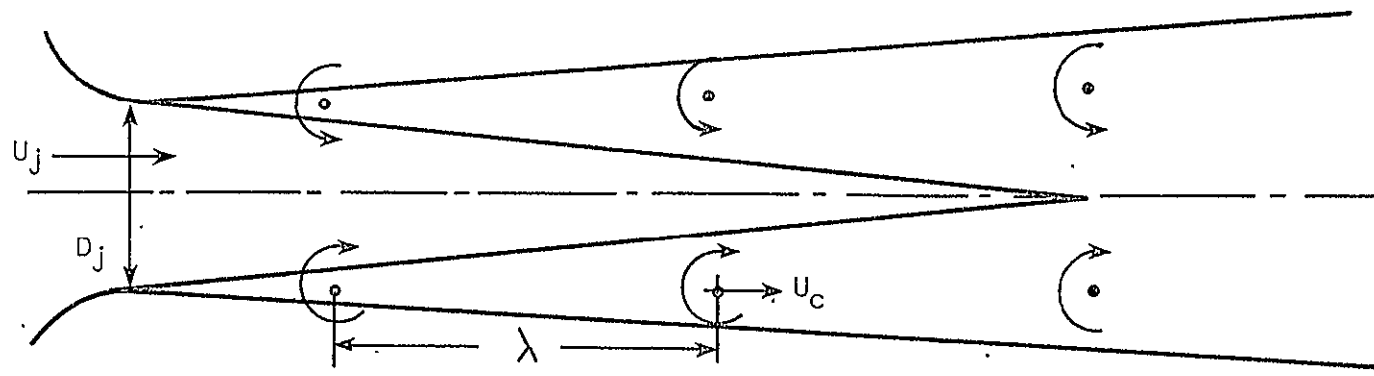


Figure 2.1.1 Vortex Model of a Circular Jet

$$S_t = fD_j/U_j$$

$$U_c = S_t \lambda / D_j$$

and λ is the average vortex ring spacing. Batchelor and Gill^[7] studied the linear stability of axisymmetric waves on a jet column, which would correspond to incipient break up of the vortex tube into individual vortices. This vortex tube at the jet exit, is found to be inherently unstable and to roll up upon itself a short distance downstream to form a vortex ring [Figure 2.1.2].^[4] Widnall and Sullivan^[8] also observed that the circular structure of the vortices is unstable, with a tendency to form circumferential lobes that are continuously changing around these vortex rings, eventually causing the rings to break up. Laufer, Kaplan and Chu^[9] presented evidence that these vortices coalesce as they move downstream. These interacting vortex rings have been found to have two major points of coalescence, 2.5 and 4.5 diameters downstream, the latter region marking the end of the potential core.^[10]

With each vortex ring is associated a low pressure, which accounts for the pressure and velocity effects in the entrainment region and in the potential core. Hot wire velocity spectra in the entrainment region and in the potential core indicate strong peaks at Strouhal number of 0.3 to 0.5. These peaks are still seen in the sheared annulus, although a low frequency component of the spectrum is also seen. Moving downstream into the adjustment zone the low frequency component dominates beginning to mask out the peak at $S_t = 0.3$. The vortex rings eventually begin to break up and become dominated by the surrounding turbulence so that they are no longer detectable in the fully developed zone.^[11]

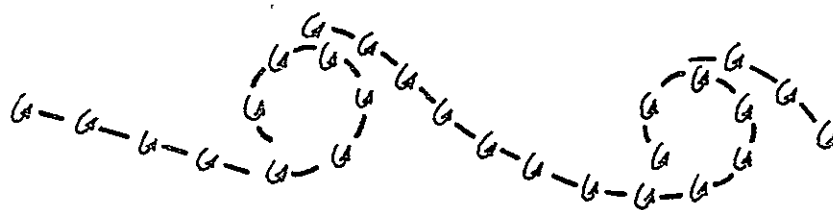


Figure 2.1.2 a) Vortex sheet Roll Up

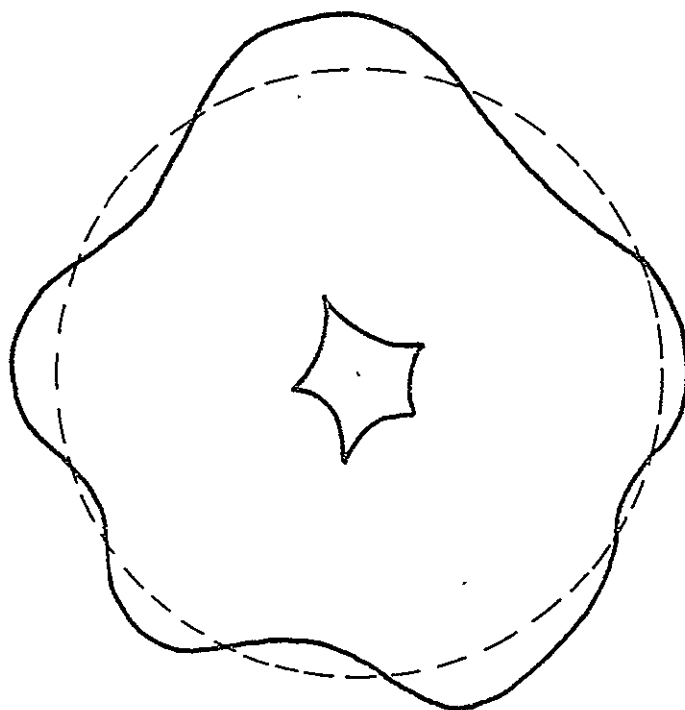


Figure 2.1.2 b) Lobed Vortex Ring

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Davies^[12] measured the first four moments of the axial velocity in the sheared annulus and back into the adjustment zone up to a distance of nine jet diameters. He found that these values were constant along constant values of the angle extended from the lip of the jet, as shown in Figure 2.1.3. He defined a new coordinate η , where $\eta = \tan \theta = (r - \frac{1}{2} D)/x$. He found that the skewness and flatness were functions of η within the limits $-0.15 < \eta < 0.2$ but that they had Gaussian values in the potential core [$\eta < -0.15$] and in the entrainment region [$\eta > 0.2$]. Through this newly defined coordinate, he was able to define the limits of the sheared annulus clearly.

Lau, Fisher, and Fuchs^[4] demonstrated that measurement of static pressures can be made with 1/4" microphones fitted with nose cones. A hot wire, measuring u_x , and the microphone were placed along side each other at the centerline of the jet and were found to have a correlation coefficient of about -0.85. When the nose cone was removed, the microphone measured total axial pressure, and the cross-correlation was about 0.90. These results conform with the vortex model as shown in Figure 2.1.4.

When the microphone and hot wire were moved to the edge of the jet, the cross-correlation value was 90° out of phase, becoming positive in the entrainment region. When hot wire was changed to measure the radial component, u_r , the pair always measured signals that were 90° out of phase. When u_r and u_x were compared, the signals measured were always near 90° out of phase, changing sign as r/D increased beyond unity. These trends are all consistent with the vortex model.

This vortex model satisfies all the inconsistencies encountered in the classical model. Thus, the vortex model is the one that was

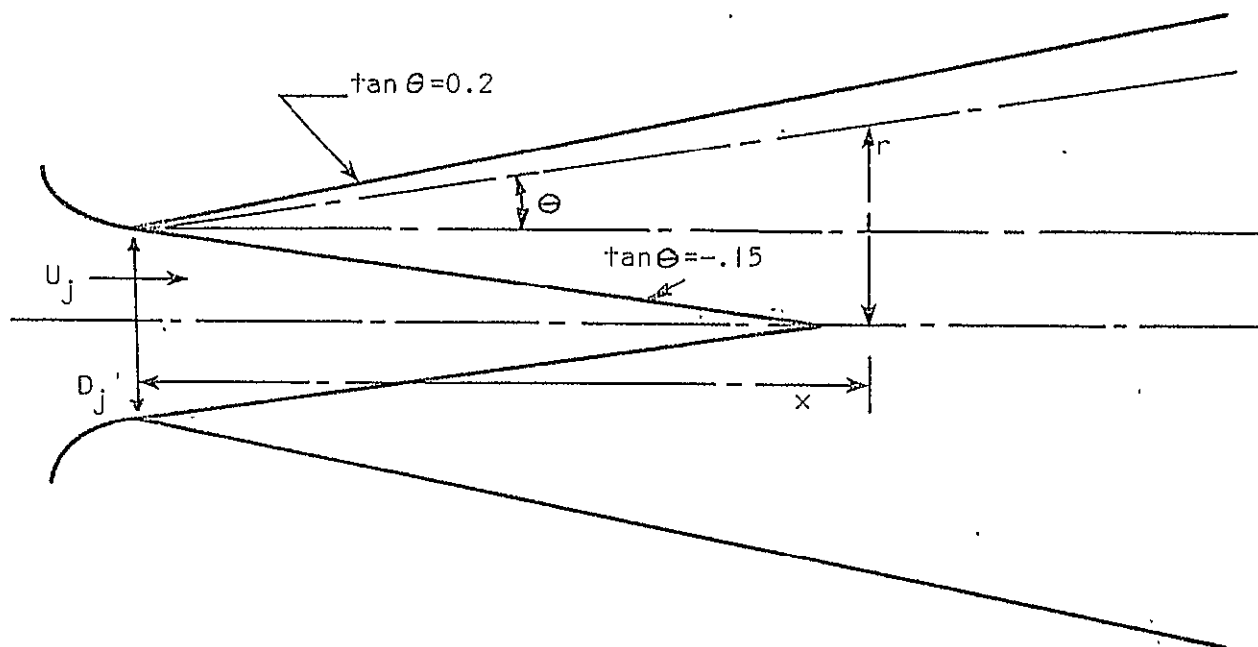


Figure 2.1.3 Limits of Sheared Annulus

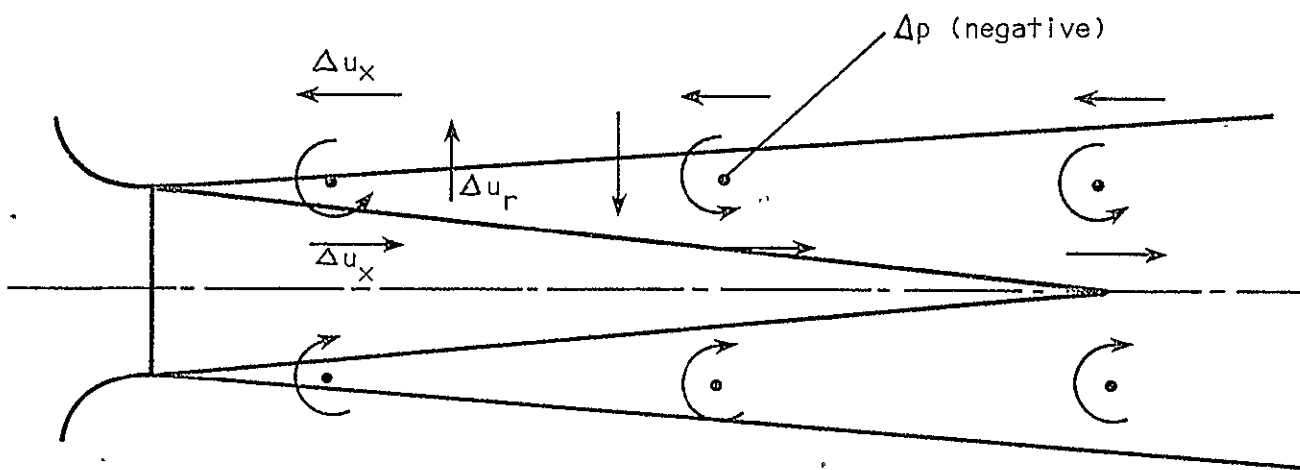


Figure 2.1.4 Vortex Model Fluctuations

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assumed throughout this report.

2.2 Scaling Laws for a Circular Jet

Meechum and Hurdle [17] measured fluctuating static pressures in a T-58 jet engine, using a 1/4 inch B&K microphone with a nose, and obtained 1/3 octave band spectra which peak between Strouhal numbers of 0.3 and 0.5, the same range as the observed model tests. Because flow conditions in a full scale jet are far from the ideal flows encountered in models, it is highly improbable that full-scale measured data will collapse as fully as do the data from model jet. However, it is believed that the full scale behavior can be predicted from suitably scaled model tests, using the scaling parameters given below:

Strouhal Number

All jet spectra should be similar when scaled on Strouhal number. The mean velocity distribution across the model should simulate the full scale values, and the overall average velocity based on total flow should be used as the reference jet velocity, U_j . When non circular jets are in USB applications, an 'effective' diameter must be found, so that test data will collapse into a single plot.

Impingement Pressure Coefficients

Dimensionless pressure coefficients ($P_{rms} / 1/2 \rho U_j^2$) measured in jet impingement should be similar, where U_j is also referenced to as the overall average velocity of the jet, as described above. Likewise, power spectral densities of pressure coefficients, when presented against Strouhal number, should collapse into one single plot.

Temperature Effects

Temperature effects of a full scale jet make it impossible to

completely scale all parameters of a coaxial jet using cold air. Therefore, two designs should be studied. By choosing the exit area so that the volume flow rates scale, it is possible to achieve a kinematically scaled design, in which convection velocities and Strouhal numbers of vortices can be scaled. The second option would be to scale dynamic pressures and mass flow ratio at the expense of kinematic scaling.

To most accurately model a full-scale jet; a coaxial jet should be used. The jet used in this work was not, however, coaxial.

Mach Number

There was an indication of a weak Mach number effect in the results of the tests on the "Beach" facility^[16]. The nature of the air blowers used in the current work made simulation of Mach numbers impossible.

2.3 Jet Impingement

Fluctuating pressures in jet impingement on a flat plate were measured by Strong, Suddon, and Chu^[13], who found values for the dimensionless fluctuating pressures $[p_{rms} / \frac{1}{2} \rho U_j^2]$. They reported results at seven diameters downstream, and found a maximum value of 0.12 on a plate normal to the flow. The values decreased with increasingly oblique angles, approaching a value of .006 which is typical of wall boundary layers. They also took pressure correlation values between the centerline of the plate and various other points. They found no evidence of vortices striking the plate, however, they never reported any measurements within the initial zone where the vortices are most prevalent.

Foss and Kleis^[14] did an extensive study with oblique impingement of an axisymmetric jet. They found that the jet is upward curved, if

impinged on a plate with slight angle from the horizontal plane. However, if the impingement angle is greater than 12° , approaching normal impingement, a complex interaction between jet curvature and jet spreading occurs. This distortion occurs primarily near the surface of the plate while the upper portion retains its axisymmetric structure. They found that streamwise vorticity is introduced into the flow field by the lateral surface pressure gradient, due to wall jet effect, and the vorticity of the approaching jet near the plate. This phenomenon accounts for the distortion of the fluctuating pressure levels measured below the jet centerline.

Westley, Wooley and Brosseau [15] studied jet impingement and found that the plate can be divided into two areas, the impingement area with fluctuating pressures similar to those of the jet, and the remaining surface with pressure fluctuations typical of a developed wall jet. They found that fluctuating pressure levels in the developed jet region were sensitive to the nozzle's separation from the flat plate, and inversely proportional to the excess nozzle pressure ratio. They found evidence of Strouhal number peaking in the energy spectra near the exit of the jet.

Full size jet tests have also been made again confirming the presence of high levels of fluctuating pressures [16]. Tests were done both on the externally blown flap [EBF] and on the upper-surface-blown flap [USB] configuration giving maximum levels of 165 dB and 157 dB, respectively. It was also found through auto-spectra analysis of fluctuating pressures, that the EBF configuration had its energy

concentration below 1000 Hz on the lower surface of the wing and below 400 Hz on the upper surface. It was determined that 0.2 is a reasonable upper limit for the dynamics pressure coefficient $[P_{rms}/q_j]$ for both configurations.

Chapter 3

INSTRUMENTATION AND DATA ANALYSIS TECHNIQUES FOR PRESSURE MEASUREMENTS

This chapter deals with the instrumentation and data analysis techniques that were developed for the investigation of fluctuating pressures behind a free jet and behind a jet impinging on a flat plate. The same techniques could be used to investigate any regions containing pressure fluctuations, however, all applications examined in this work were behind a cold jet at relatively low velocities. Measurement of pressure fluctuations about the mean was of primary interest and encompasses the majority of the data collected. A limited amount of mean pressures were measured.

Several forms of data analysis were used and are explained in this chapter. Of these, Fast Fourier Transform [FFT] analysis of correlations was the principal method of data reduction, and this is explained in detail because of its importance.

All pressure fluctuations are expressed in decibels referenced to the dynamic pressure at the jet exit, q_j , $(10 \log_{10} p_{rms}^2 / q_j^2)$ and the frequency, f , is expressed in non-dimensional Strouhal number form ($S_t = fD_j / U_j$). These dimensionless parameters are used in order to help in the derivation of scaling laws based on jet exit velocity and jet diameter.

3.0 Flow and Traverse System

The flow was created by a cold jet having a circular cross-section nozzle, with exit diameter of 3.17 cm. The traverse system used enabled

investigation of the jet by a single pressure probe or by two probes simultaneously.

The jet consisted of a Staco adjustable AC voltage supply attached to line voltage, a Rotron centrifugal blower, outlet duct, flow straightening screen sections and a converging nozzle [Figure 3.0.1]. The adjustable power supply enabled the jet exit velocity to be varied up to a maximum of about 36 m/s. The flow straightening section was a plenum 60 cm long and containing three fine-meshed screens roughly 5 cm apart. A pressure port was located in this plenum chamber, and the mean static pressure measured at this port was shown to have the same value as the dynamic pressure, q_j , measured at the jet exit. The fiberglass nozzle had a contraction ratio of approximately 22 to 1 giving the desired "top hat" profile at the jet exit.

The jet was secured upon a lathe bed which contains an adjustable table [Figure 3.0.2]. This table has two degrees of freedom, it can be moved along the axis of the jet and radially across the jet, making it possible to survey the different regions of the jet. Another traverse can be mounted on this table when two probes are used simultaneously. The second traverse adds two more degrees of freedom, one in the radial, the other in the axial directions, so that one probe can be moved relative to the other to obtain such quantities as convection velocity, correlation coefficients, and cross-correlations.

3.1 Pressure Sensors

Pressure probes placed in the flow system were used to measure mean pressures and pressure fluctuations about these mean pressures.

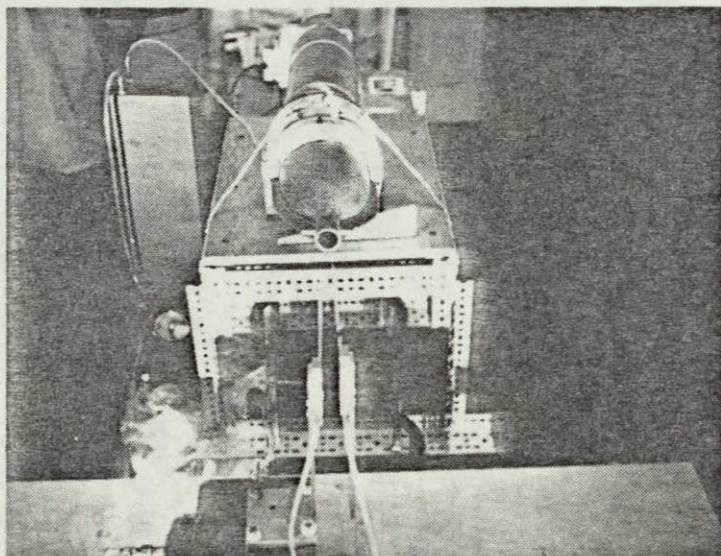
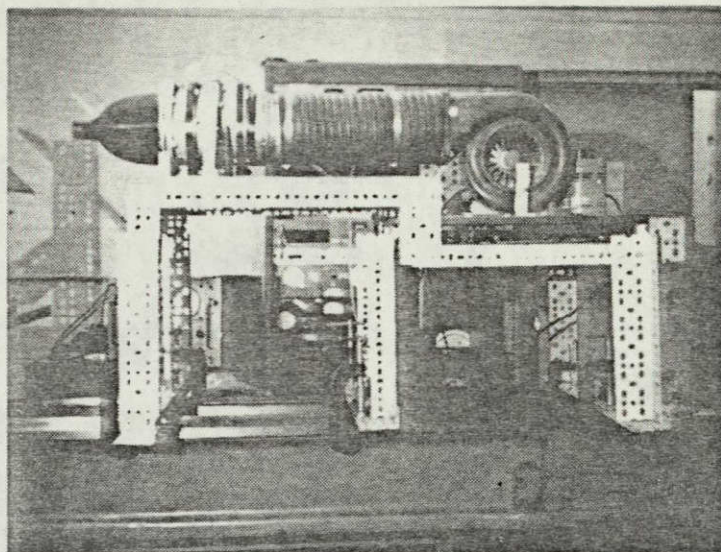


Figure 3.0.1 Cold Jet Assembly

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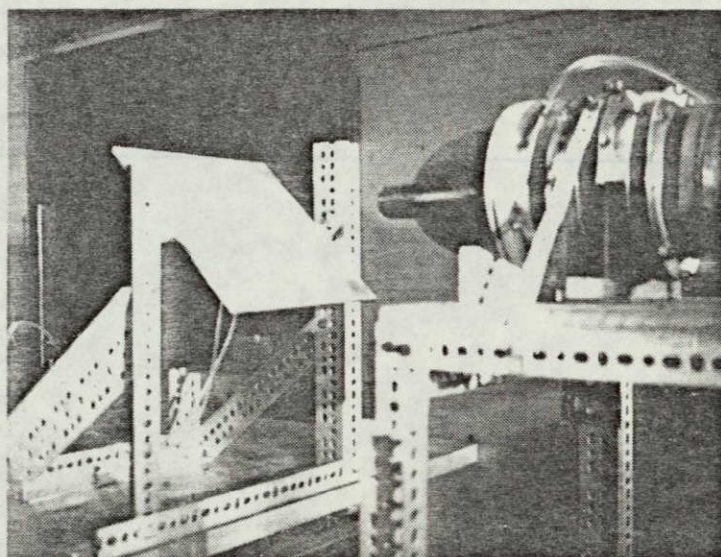
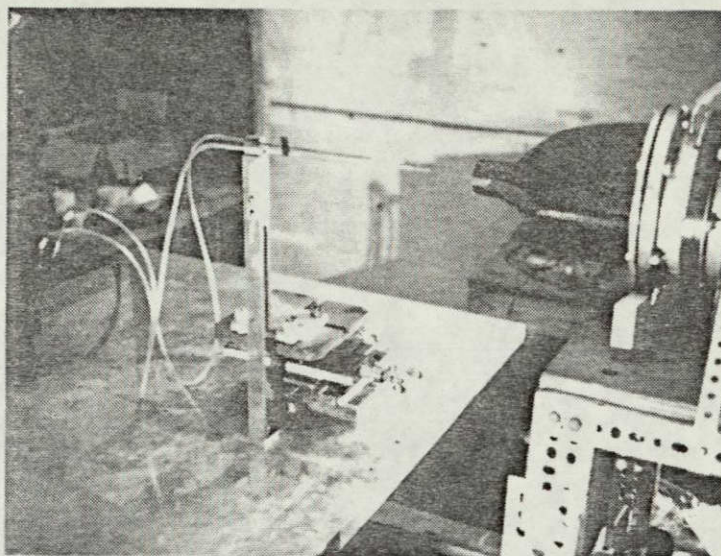


Figure 3.0.2 Data Acquisition Set-Up

The fluctuating pressures were of primary concern.

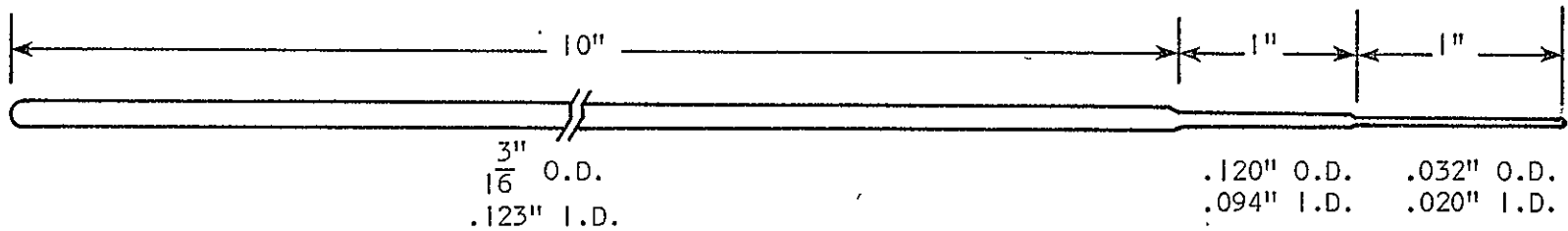
The mean pressures were measured by attaching a pressure probe to a manometer. In most cases, fluctuating pressures were measured by pressure probes connected through 1/8 in (3.175 mm) inner diameter plastic tubing to Bruel and Kjaer Type 4148 1/8 in (3.175 mm) condenser microphones. It is important to realize that the pressure sensed by the pressure probes and the pressure measured by the microphone will be altered by the transfer function of the probe and of plastic tubing.

These transfer functions are studied in detail in Chapter 4.

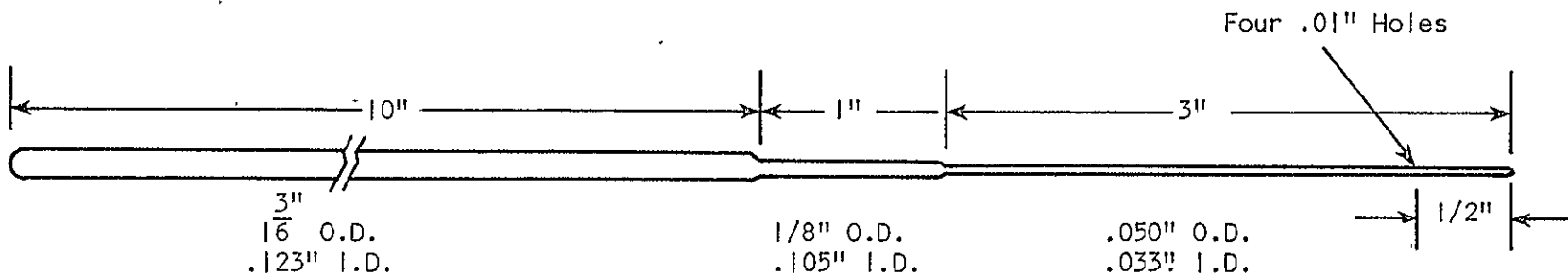
Several different types of pressure probes were used. Originally an investigative survey of the free jet was made using a conventional 1/8 in (3.175 mm) pitot probe. After satisfactory results had been obtained with these probes, hypodermic total pressure probes and hypodermic static probes were made to the designs in Figure 3.1.1, and were used in all later measurements.

Fluctuating pressures of jet impingement were studied. A flat plate containing many pressure ports was made to the design in Figure 3.1.2. The plate can be moved on the traverse system and the inclination angle, β , can be varied to give a complete variation of the significant parameters.

Kulite 1/8 in (3.175 mm) CQ-125 Ultra-miniature pressure transducers and flush mounted 1/8 in (3.175 mm) B&K microphones were also used to measure fluctuating pressures on a flat plate. These were mounted on a special plate to facilitate comparisons between different pressure sensors [Chapter 4]. A homemade amplifier featuring Fairchild operational amplifier, was used for the kulite transducers to amplify their output.



Total Pressure Probe



Static Pressure Probe

Figure 3.1.1 Pressure Probes

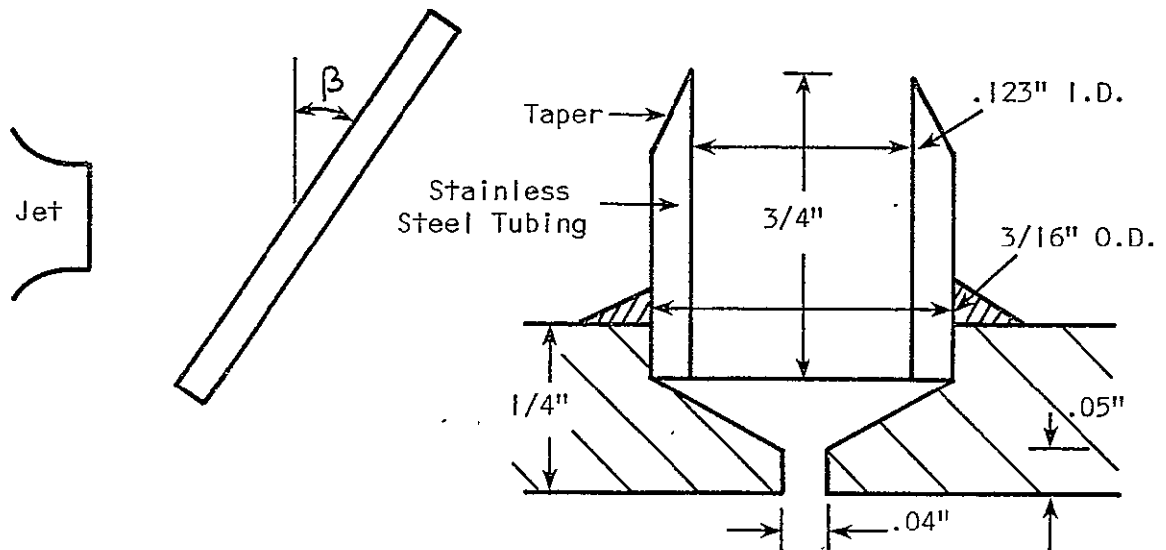
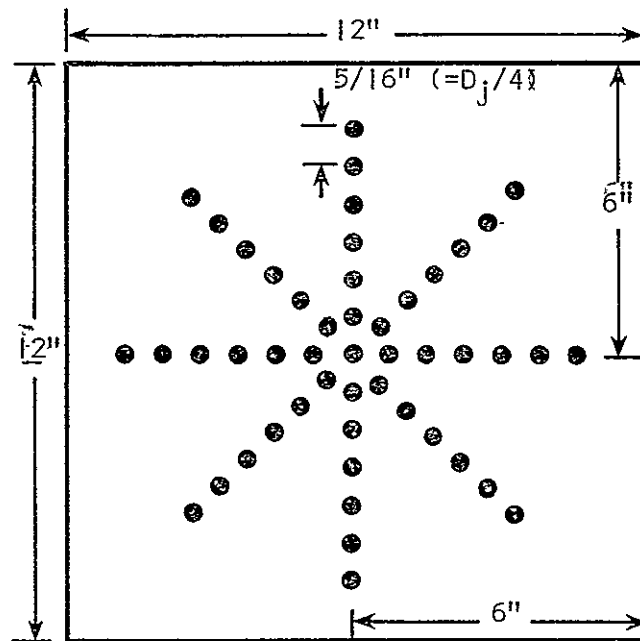


Figure 3.1.2 Flat Impingement Plate

about 1000:1 to obtain useful output voltages.

3.2 Data Analysis Equipment

Two different data analysis procedures were used to measure fluctuating pressures (p_{rms}). In one procedure, a B&K type 2113 Audio Frequency Spectrometer was used in conjunction with pressure sensors to measure fluctuating pressures. The calibration for the 2113 came from a B&K Type 4220 Pistonphone which supplies a constant 124 dB, 250 Hz signal to the microphone. This system measures the overall p_{rms} level in decibels, however, it is referenced to p_{ref} ($= 2 \times 10^{-5} \text{ N/m}^2$). To reference the measured value to q_j , the dynamic head in the jet, a constant term of $20 \log_{10} \frac{q_j}{p_{ref}}$ was subtracted. The spectrometer was also connected to a B&K type 2305 level recorder to give 1/3 octave spectral levels for center band frequencies of 35 Hz to 20 kHz. These frequencies were then converted to Strouhal number.

In the second procedure, a Federal Scientific Model UC 202-B Ubiquitous Correlator was used for analyzing pressure fluctuations. This correlator provides 512 point correlations to an accuracy of 9 binary bits plus sign, however, procedures can be used to obtain double precision accuracy of 18 bits plus sign. The input from the 1/8 inch microphones into the correlator went through B&K preamps and through a Nagra SJ recorder. [The tape recorder is used so that internal electrical transfer functions are identical for simultaneous analysis of two probes.]

In making readings, the zero time point was delayed one half time window, so that positive and negative correlation intervals were obtained. Seven readings were made for each analysis:

Channel 1 & 2 calibration signal [from pistonphone].

Channel 1 & 2 noise with everything on except jet

Channel 1 & 2 pressure sensor signals

Cross-correlation of channels 1 & 2

This is the most general case when two probes are used. When a single probe is used, only the three readings on channel 1 are needed. The output voltage from the correlator varies from -5 volts to +5 volts and can be displayed on an oscilloscope or reproduced on an x-y plotter. For determination of correlation coefficients, a Fluke Digital Voltmeter was used to obtain direct readings.

Alternatively, all readings can be transferred from the correlator storage to paper tape output of a teletype for input to the CROSSPECT Fast Fourier Transform (FFT) program on the CDC 6400 computer. These readings are preceded by manually inserted information about settings of the correlator, and the gain settings on the amplifiers. Using the inserted data, plus the mean square calibration readings [the zero point auto-correlations of the calibration signals] the remaining data can be scaled, and the following can be calculated in decibel/phase form in the CROSSPECT program:

Channel 1 & 2 auto-spectra of signals and background noise

Cross-spectra of Channels 1 & 2

The computer prints out and plots the signal and noise auto spectra for both channels, as well as the transfer function magnitude and phase, and the coherence. All of this data is in decibels and degrees, the spectra being in decibels referenced to q_j , and the frequency being given in Strouhal number form. A more detailed analysis of the FFT

output and model used, is in the following section.

3.3 Fast Fourier Transform Analysis

The CROSSPECT program used for FFT analysis of fluctuating pressure data is shown in Figure 3.3.1. The input I is from the coherent part of the turbulent structure of the jet flow, and this is modified by two hypothetical "external" transfer functions TE_1 and TE_2 before arriving at the two pressure sensors. Additional uncorrelated pressure disturbances, n_1 and n_2 are also felt at these probes. Although these are truly pressure disturbances, which add to the total pressures, they are treated analytically as incoherent noise.

Between the pressure sensors and the B&K 1/8 in (3.175 mm) microphones, the pressure disturbances are further modified by "internal" transfer functions TI_1 and TI_2 . Later, during the analyses performed by CROSSPECT, these transfer functions are predicted analytically as the "calculated" transfer functions TC_1 and TC_2 , and these are used to cancel the effect of the internal transfer function. [TI_1 and TI_2 are typically the transfer functions introduced by the probes and by the plastic tubing. In the next chapter, these transfer functions are derived, and it is shown how they can be input as TC_1 and TC_2 to cancel out the effect of the tubing before the one-sided spectra are printed out.] Finally, output of the two transducers is obtained on channels 1 and 2 as O_1 and O_2 .

The input to CROSSPECT is the three correlations R_{11} , R_{22} , and R_{12} , together with the calibration auto-correlation RC_{11} , and RC_{22} , as well as the background electronic noise auto-correlations Rn_{11} and Rn_{22} .

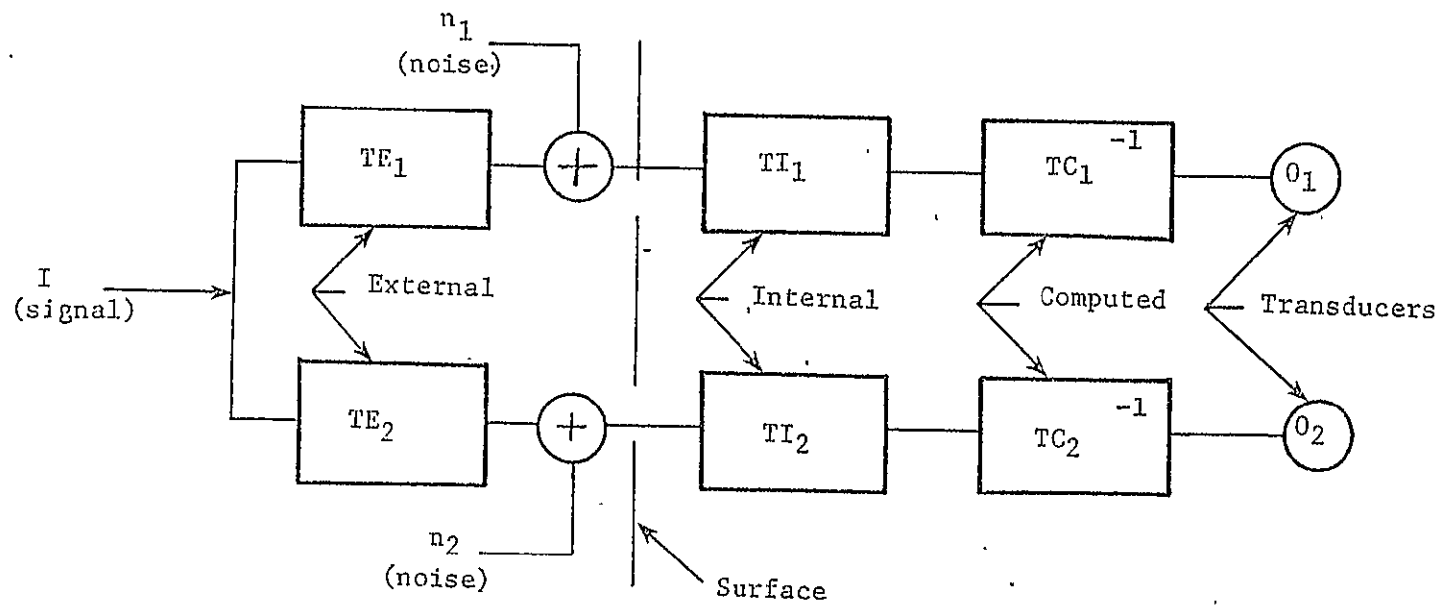


Figure 3.3.1 CROSSPECT Model

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Each correlation is given for 512 time steps.

CROSSPECT obtains the Fast Fourier Transforms of these auto-correlations, corrects them for instrumentation settings, calibration levels, and calculated transfer functions TC_1 and TC_2 to obtain the three one-sided spectra G_{11} , G_{22} , and G_{12} , for 257 frequency steps including zero frequency. At the same time, auto spectra are obtained of the electronic noise, $G_{n_{11}}$ and $G_{n_{22}}$.

By definition

$$G_{AB}(f) = \langle \bar{A}(f) \bar{B}^*(f) \rangle_N$$

where $\bar{A}(f)$ is the frequency dependent Fourier transform of $A(t)$, $\langle \rangle_N$ denotes the mean value of N samples, and $*$ denotes the complex conjugate. Here, N is the number of measurements which is selected on the correlator.

The transform of the output signals in Figure 3.3.1 are

$$\bar{O}_1 = TC_1^{-1} TI_1 (TE_1 \bar{I} + \bar{n}_1)$$

$$\bar{O}_2 = TC_2^{-1} TI_2 (TE_2 \bar{I} + \bar{n}_2)$$

Thus, on substitution into the expression for G_{AB} , and noting that, by definition of noise,

$$G_{In_1}, G_{In_2}, G_{n_1 n_2} \rightarrow 0 \\ N \rightarrow \infty$$

it is found that, within small variances resulting from large finite values of N

$$\begin{aligned} G_{11} &= |TC_1|^{-1/2} |TI_1|^2 \left(|TE_1|^2 G_{II} + G_{n_1 n_1} \right) \\ G_{22} &= |TC_2|^{-1/2} |TI_2|^2 \left(|TE_2|^2 G_{II} + G_{n_2 n_2} \right) \\ G_{12} &= (TC_1)^{-1} (TC_2^*)^{-1} TI_1 TI_2^* TE_1 TE_2^* G_{II} \end{aligned}$$

The variance on the magnitude of G , where G represents G_{11} , G_{22} , or G_{12} is

$$\varepsilon_G = \sigma_G / M_G = 1 / \sqrt{2BT}$$

where σ_G is the standard duration and M_G is the mean value of G , B is the bandwidth which is the inverse of the correlator window W , and T is the total time duration of the measurement.

For the UC-202B correlator,

$$\varepsilon_G = \sqrt{\frac{M}{2N} \frac{\text{Min}(W/100, 1)}{\text{Min}(W/100, 1)}}$$

where M (≈ 512) is the number of time steps [18,19].

The coherence of the two output signals is given by

$$(\gamma_{12})^2 = \frac{|G_{12}|^2}{G_{11}G_{22}}$$

Thus, if an overall transfer function T_{12} is defined by

$$T_{12} = \frac{(TC_1)^{-1} TI_1 TE_1}{(TC_2)^{-1} TI_2 TE_2}$$

and if the signal to noise ratios at the pressure probes are defined by

$$SN_1 = |TE_1|^2 G_{II}/G_{n_1 n_1}$$

$$SN_2 = |TE_2|^2 G_{II}/G_{n_2 n_2}$$

it can be shown that

$$(\gamma_{12})^2 = 1/(1 + 1/SN_1) (1 + 1/SN_2)$$

then, from the previously derived expressions for the spectra

$$T_{12} = \frac{1}{(1 + 1/SN_1)} \frac{G_{11}}{G_{12}^*} = (1 + 1/SN_2) \frac{G_{12}}{G_{22}}$$

so that the true magnitude of T_{12} is known between the following limits

$$|G_{12}| / G_{22} < |T_{12}| < G_{11} / |G_{12}|$$

However, because G_{12} is the only complex quantity in the equation for T_{12} , the phase angle of T_{12} is known.

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The geometric mean of the two limits, $\overline{|T_{12}|}$, is also the value of $|T_{12}|$ when the two signal to noise ratios are equal. It is given by

$$\overline{|T_{12}|} = \sqrt{G_{11}/G_{22}}$$

Thus, the limits on $|T_{12}|$ can be defined in terms of $(\gamma_{12})^2$, the coherence, so that

$$\gamma_{12} \overline{|T_{12}|} < |T_{12}| < \frac{1}{\gamma_{12}} \overline{|T_{12}|}$$

Converting G_{12} to decibel/phase notation, gives

$$LG_{12} = 10 \log_{10} |G_{12}| \sim 10 \log_{10} (q_j^2)$$

where q_j is the reference dynamic pressure. Also, the phase angle of G_{12} is

$$\theta G_{12} = \tan^{-1} \left[\frac{\mathcal{I}\{G_{12}\}}{\mathcal{R}\{G_{12}\}} \right]$$

where $\mathcal{R}\{\}$ and $\mathcal{I}\{\}$ stand for real and imaginary part of, respectively.

Thus,

$$\theta G_{11} = \theta G_{22} = 0$$

The variance on LG (i.e., LG_{11} , LG_{22} , or LG_{12}) is given in decibels by

$$\begin{aligned} LVG &= 10 \log_{10} (1 + \epsilon_G) \\ &= 69.5 \sqrt{\frac{\text{Min}(W, 100, 1)}{2^{\log_2 N}}} \end{aligned}$$

so that the one-sigma or 68% confidence limits on LG are

$$LG \pm LVG$$

For the values of N and W generally used, LVG is about .136 dB. Then, expressing the transfer function in decibels

$$\overline{LT}_{12} = \frac{1}{2} (LG_{11} - LG_{22})$$

$$\theta T_{12} = \theta G_{12}$$

Also, expressing the coherence in decibels as $L(\gamma_{12})^2$

$$L(\gamma_{12})^2 = 2LG_{12} - LG_{11} - LG_{22}$$

so that the true level of the transfer function LT_{12} varies between the limits

$$\overline{LT_{12}} + \frac{1}{2} L(\gamma_{12})^2 < LT_{12} < \overline{LT_{12}} - \frac{1}{2} L(\gamma_{12})^2$$

This equation emphasizes the significance of the coherence as the range of uncertainty is the magnitude of the transfer function.

It is important to realize that if the tubing lengths are identical then TI_1 equals TI_2 . If this is true, the magnitude and phase of the transfer function, and the coherence, are accurate and unaffected by this internal transfer function.

All spectral output of CROSSPECT is referenced to q_j and the frequency scale is changed to Strouhal number form. Normally, to present the power spectral density of pressure vs frequency, it would be calculated in units of $N^2/m^4/Hz$, so that the area under the curve would be p_{rms}^2 . To present the spectral density of pressure coefficient against Strouhal number, the previous values have to be divided by q_j^2/f_{ref} [where f_{ref} is the value of frequency when Strouhal number equals one], so that the area under the curve is now $(p_{rms}/q_j)^2$. Therefore, when the dimensionless values are presented in decibels, the reference quantity for spectral density is q_j^2/f_{ref} or, in decibel form, $10 \log_{10}(q_j^2/f_{ref})$. Examples of the output from CROSSPECT are given in Chapter 4.

Chapter 4

EVALUATION OF DATA ANALYSIS TECHNIQUES AND PRESSURE SENSORS

4.0 Evaluation of Data Analysis Techniques

Fluctuating pressures were measured, using two static probes behind the jet, to evaluate the CROSSPECT program. Channel 1 and 2 inputs into the correlation were from probes located on the jet centerline, 9.0 cm and 11.0 cm downstream, respectively. Figures 4.0.1-4.0.4 show the complete plotter output from CROSSPECT, giving two power spectra, two background level spectra, transfer function amplitude and phase angle, and the coherence. [The peaks and valleys in the auto-spectra are caused by the tubing system transfer function.]

The wild fluctuations at the larger Strouhal numbers are the result of reaching the limit of the instrumentation dynamic range. It was found that this dynamic range is about 27 dB, which can be attributed to the fact that the correlator outputs only nine bits plus sign. Internally, however, the correlator has a capacity of 27 bits per word. The ten bits [nine bits plus sign] that are used, are selected by the operator so that maximum output without overflow is obtained. The CROSSPECT program is capable of accepting an additional nine bits of data, which has the potential of increasing the dynamic range another 27 dB. When this procedure was tried, the dynamic range was found to increase by only about 3-6 dB [shown in Figures 4.0.5 and 4.0.6]. There seem to be further limitations, internal to the instrumentation, that are not readily apparent. Since the increase in dynamic range is fairly insignificant at the expense of considerable effect, this

CROSSPECT OUTPUT - RUN NO. 23

CHANNEL 1. -STATIC PROBE-9.0 CM

FULL LINE/AUTO SPECTRUM, RMS. DB.= -51.48

DASH LINE/NOISE LEVEL, RMS. DB.= -68.37

QREF= 152.00 DB./REF. FREQ. IN HZ.= 1116.00

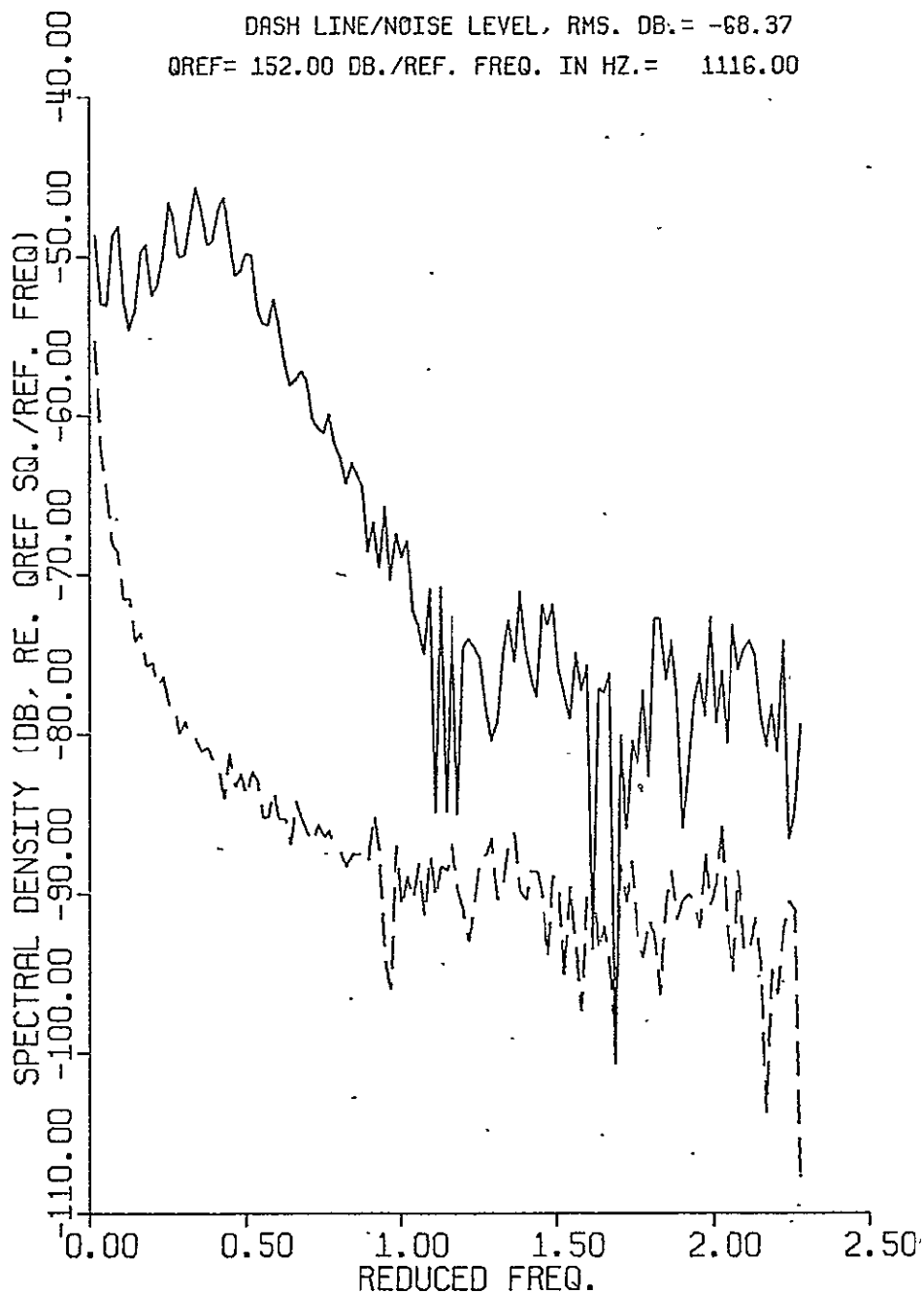


Figure 4.0.1 Power Spectra from 9.0 cm Downstream Location

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CROSSPECT OUTPUT - RUN NO. 23

CHANNEL 2. -STATIC PROBE-11.0 CM

FULL LINE/AUTO SPECTRUM, RMS. DB.= -45.29

DASH LINE/NOISE LEVEL, RMS. DB.= -69.03

QREF= 152.00 DB./REF. FREQ. IN HZ.= 1116.00

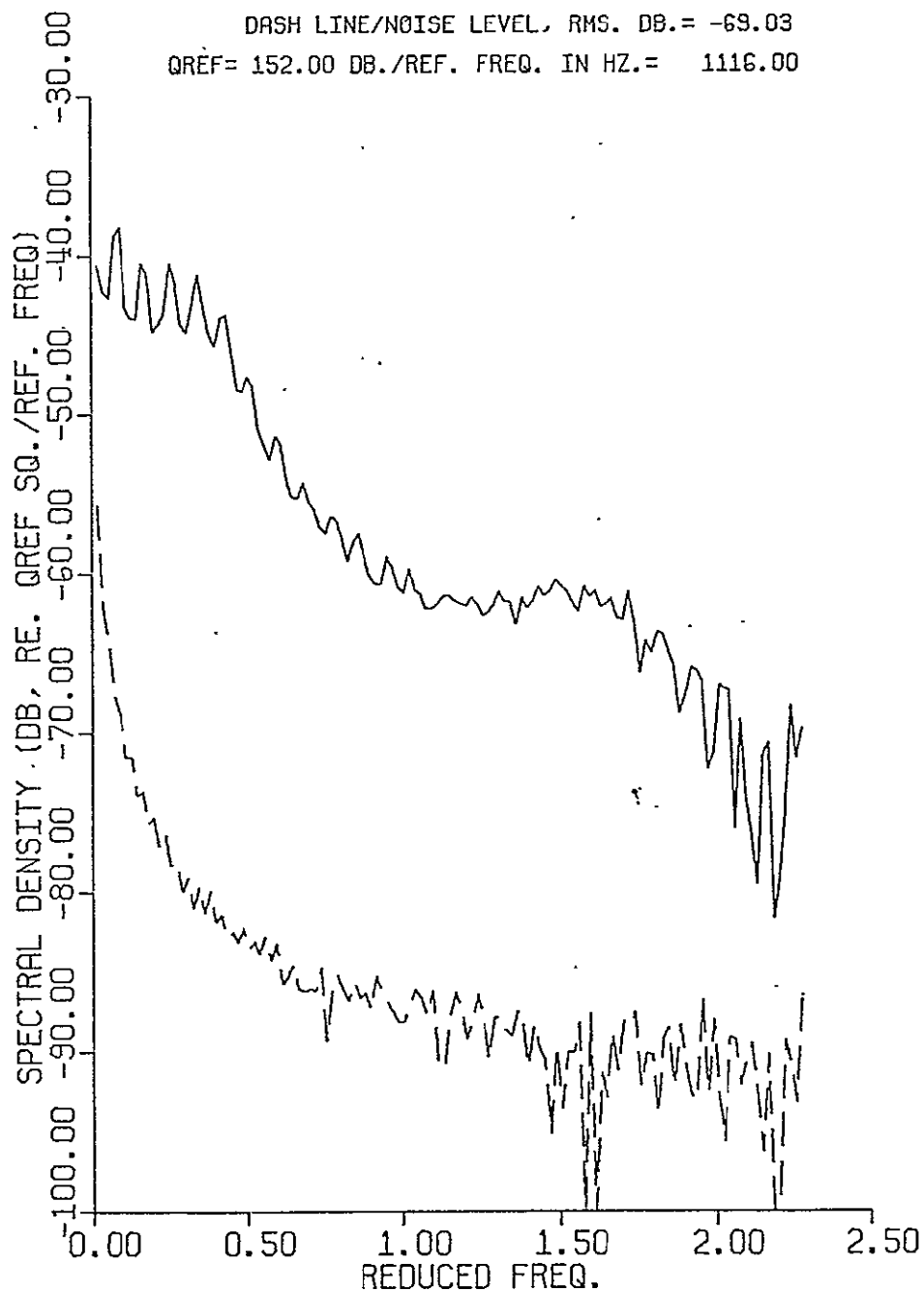


Figure 4.0.2 Power & Spectra from 11.0 cm Downstream Location

CROSSPECT OUTPUT - RUN NO. 23

TRANSFER FUNCTION AMP., CHAN. 1/CHAN. 2

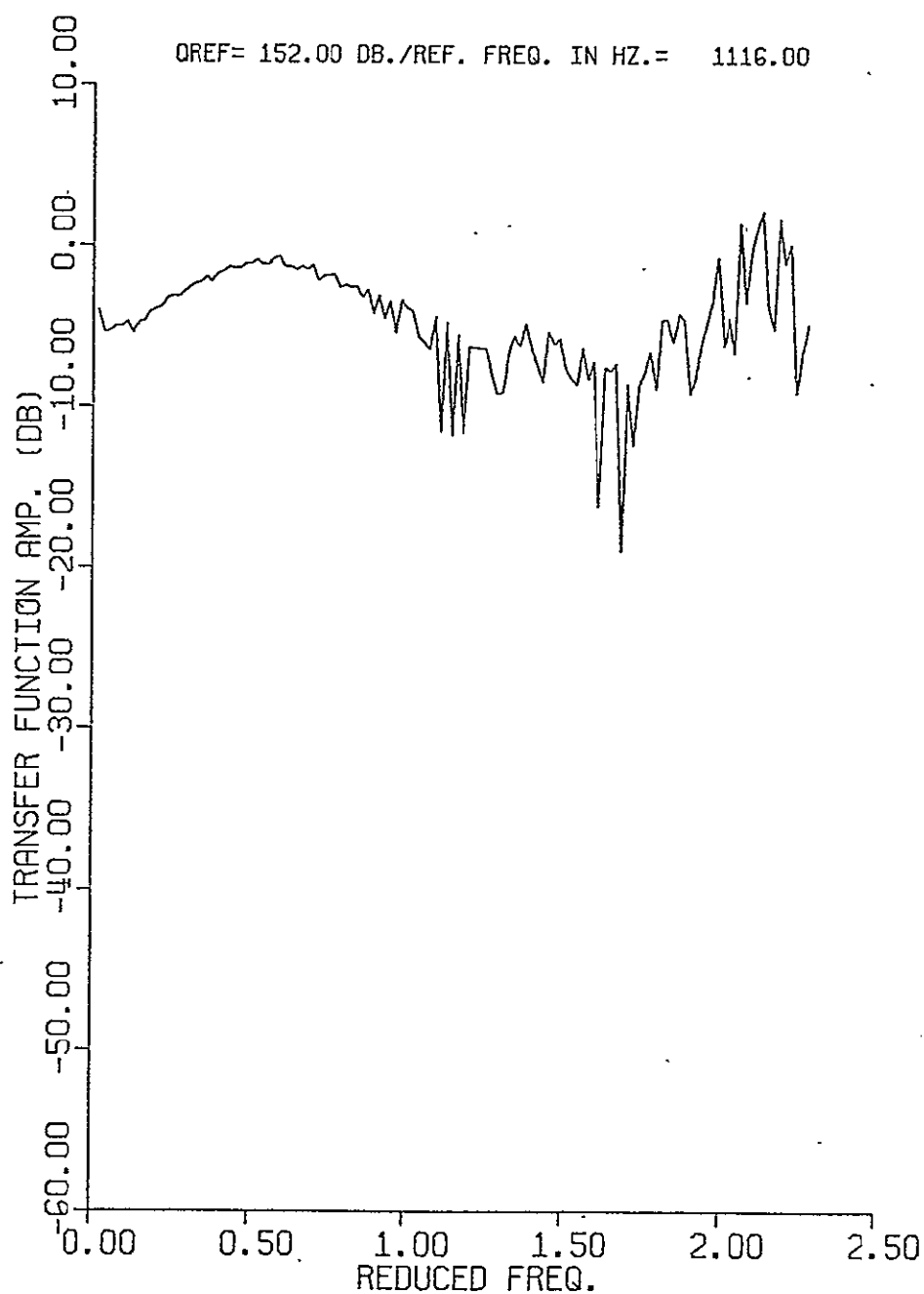


Figure 4.0.3 Transfer Function Amplitude Output

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CROSSPECT OUTPUT - RUN NO. 23

PHASE ANGLE (CH. 1 - CH. 2) AND COHERENCE

OREF= 152.00 DB./REF. FREQ. IN HZ.= 1116.00

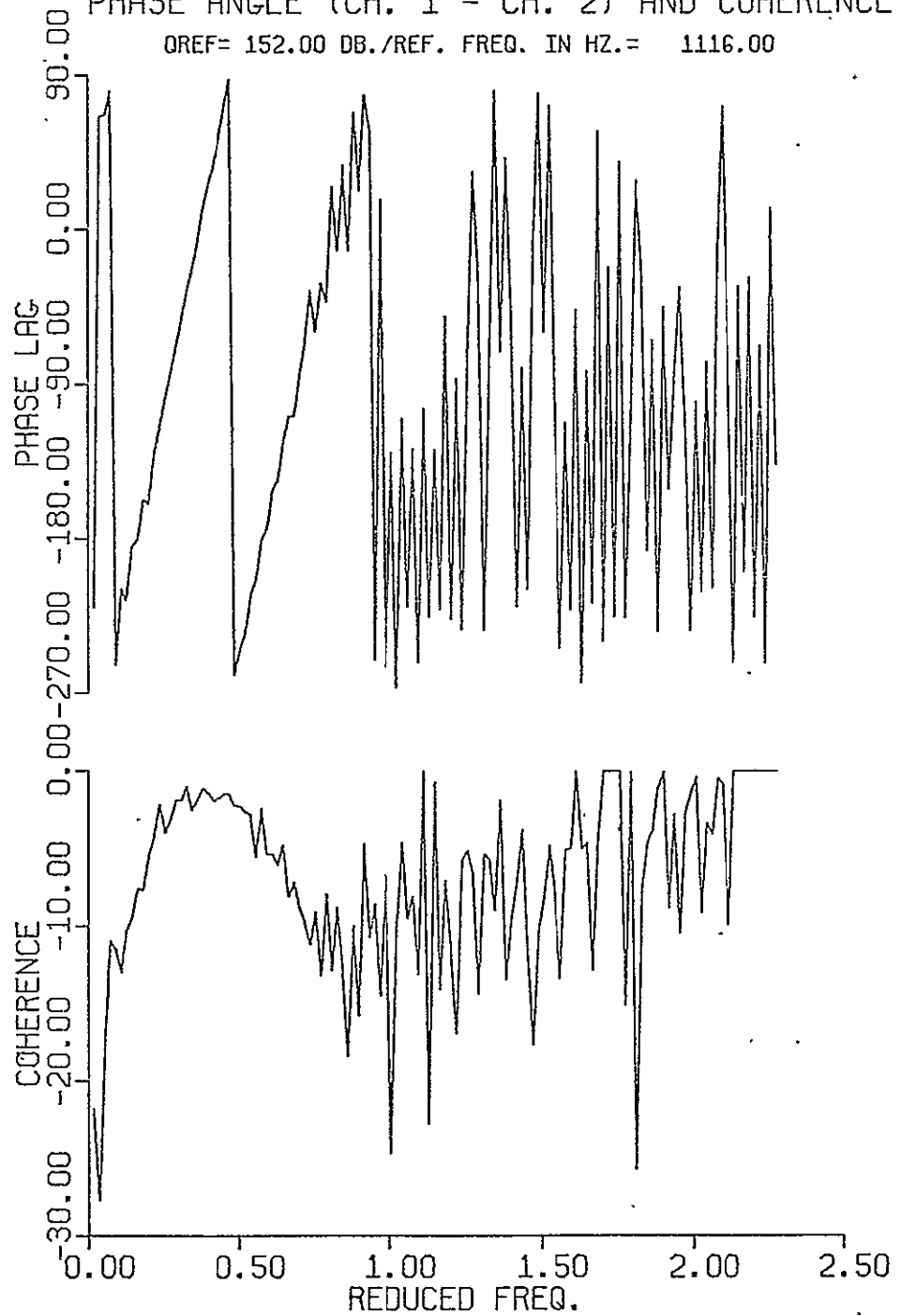


Figure 4.9.4 Phase Lag and Coherence Outputs

OLD DYNAMIC RANGE-CROSSPECT7 - RUN NO. 23

CHANNEL 1. -STATIC PROBE-9.0 CM.

FULL LINE/AUTO SPECTRUM, RMS. DB.= -51.48

DASH LINE/NOISE LEVEL, RMS. DB.= -68.37

OREF= 152.00 DB./REF. FREQ. IN HZ.= 1116.00

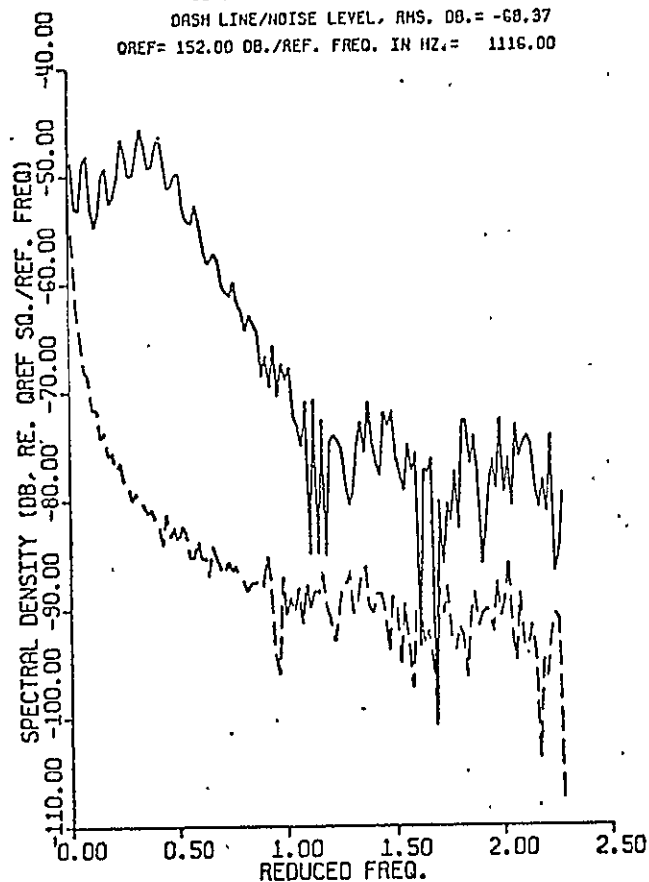


Figure 4.0.5

Power Spectra from Normal Dynamic Range

NEW DYNAMIC RANGE-CROSSPECT7 - RUN NO. 23

CHANNEL 1. -STATIC PROBE-9.0 CM.

FULL LINE/AUTO SPECTRUM, RMS. DB.= -51.55

DASH LINE/NOISE LEVEL, RMS. DB.= -68.37

OREF= 152.00 DB./REF. FREQ. IN HZ.= 1116.00

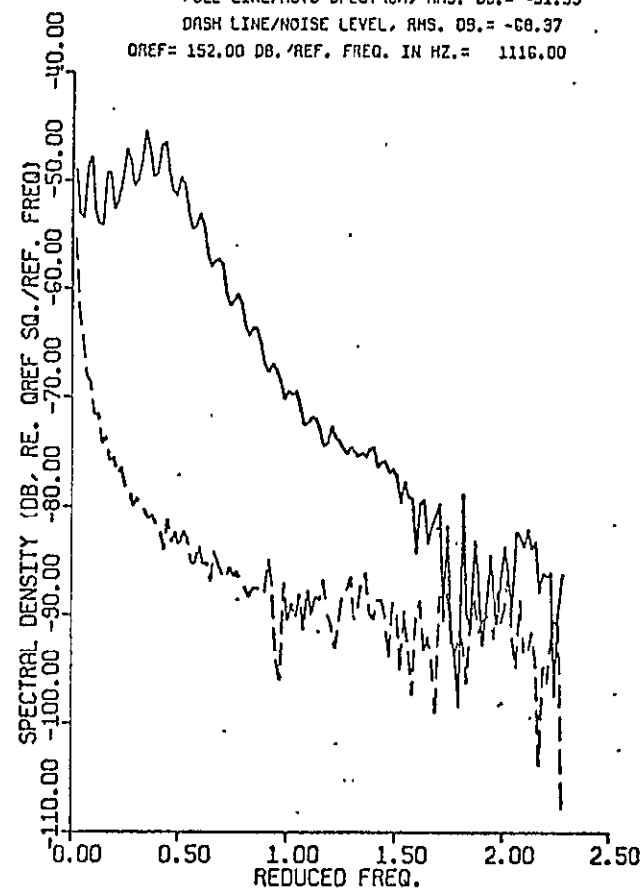


Figure 4.0.6

Power Spectra from Extended Dynamic Range

procedure was not used in obtaining the results reported in this work.

The CROSSPECT computer program has the capability of artificially adding zeros to both sides of the correlator input. This has the effect of increasing the time window, and thus reducing the frequency interval, and providing a more detailed spectral plot. This approach has been used for presenting some of the data. However, in order to make comparisons simpler, a fixed frequency scale was used for presenting most of the data, and the high frequency noise was allowed to remain on the plots.

Measurement of pressure fluctuations were taken 2 diameters downstream on the jet axis, to compare a 1/3 octave spectrum and the CROSSPECT spectrum [Figures 4.0.7 and 4.0.8]. The 1/3 octave spectrum shows a definite Strouhal number peaking [$S_t = .456$], comparing favorably to other literature. However, there seems to be almost no peaking in the CROSSPECT spectrum. Figure 4.0.9 shows how these two spectra compare after the 1/3 octave spectrum has been converted to the same constant bandwidth as the digital spectrum. Obviously, these two spectra are identical, illustrating some of the importances of each method.

The 1/3 octave spectra are most useful for showing the dependence of energy levels on Strouhal number. The digital technique is most useful in that it is capable of supplying cross-correlation information. This cross-correlation capability makes it possible to calculate quantities such as coherence, phase lags (used to obtain convection functions), transfer functions (used to make spectral comparisons), and correlation coefficients. ~~and correlation coefficients.~~

4.1 Theoretical Pressure Sensor Transfer Functions

The model assumed for calculation of the transfer functions is

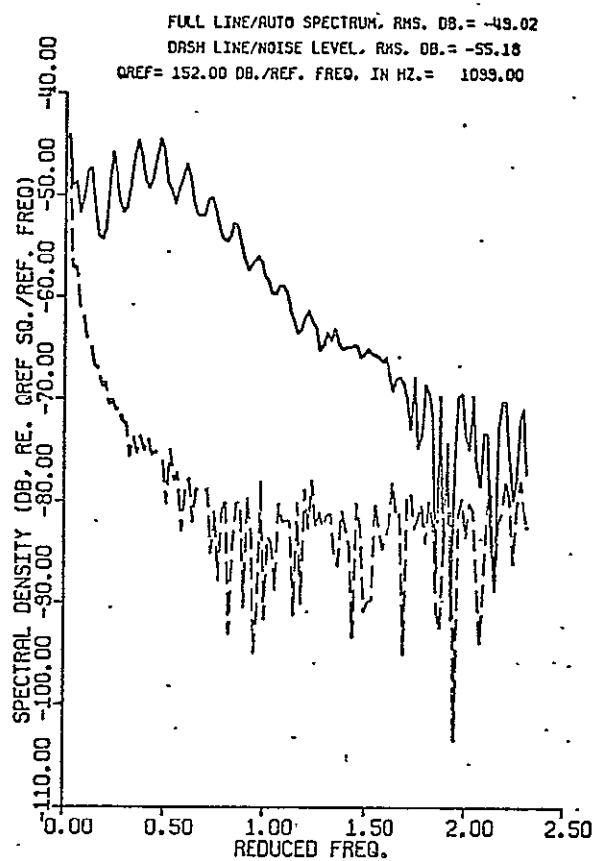


Figure 4.0.7. - Power Spectra Output From CROSSPECT

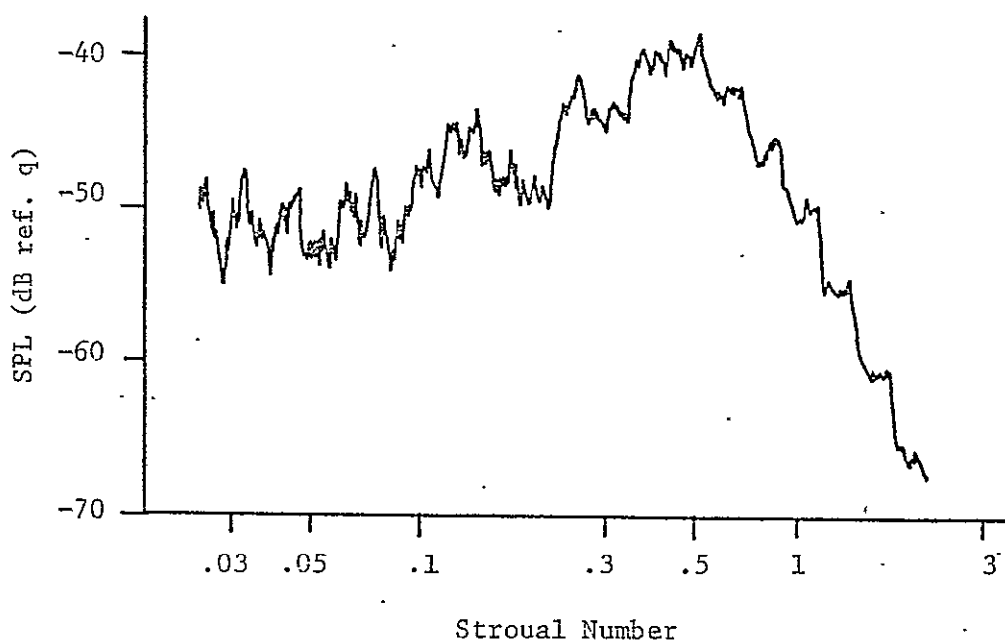


Figure 4.0.8 - 1/3 Octave Spectra

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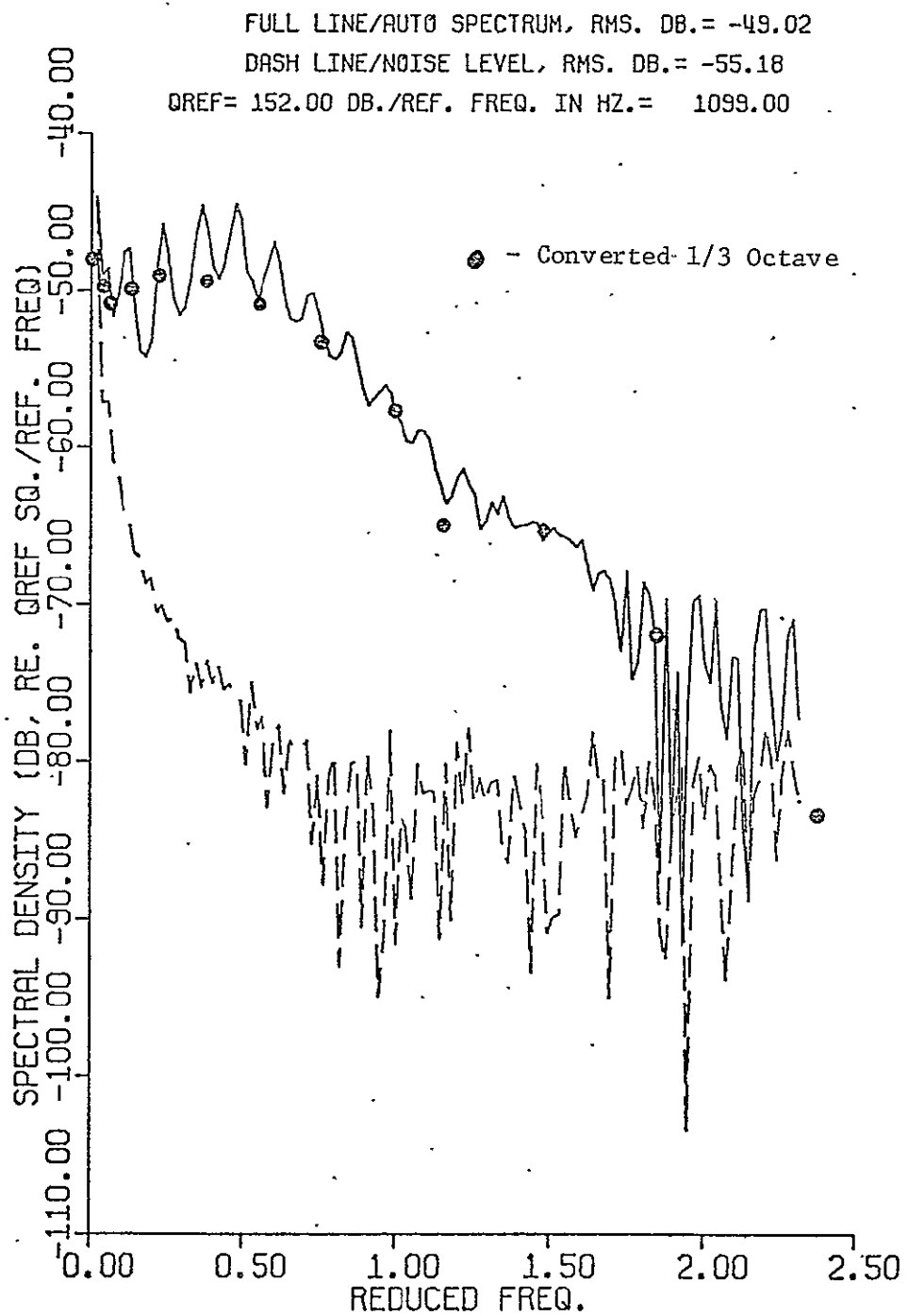


Figure 4.0.9 - Comparison Between Power Spectra
and 1/3 Octave Spectra

shown in Figure 4.1.1. This model represents a microphone connected through plastic tubing to a pressure probe. The external pressure to be measured is represented in its complex form by $P_E e^{i\omega t}$ and the pressure measured by the microphone is given as $P_M e^{i\omega t}$. The ratio of complex pressures, P_M/P_E is the desired transfer function, T.F.

The equations of wave propagation are:

$$p(x,t) = \left\{ P_R e^{-ikx} + P_L e^{ikx} \right\} e^{i\omega t}$$

$$u(x,t) = \left\{ \frac{P_R}{\rho c} e^{-ikx} - \frac{P_L}{\rho c} e^{ikx} \right\} e^{i\omega t}$$

and boundary conditions at $x=0$ are:

$$p(0,t) = P_M e^{i\omega t}$$

$$\dot{u}(0,t) = -(P_M/Z_M) e^{i\omega t}$$

leading to the following relationships at $x=0$

$$P_M = P_R + P_L$$

$$-P_M/Z_M = P_R/\rho c - P_L/\rho c$$

Solving for P_L and P_R

$$P_L = \frac{1}{2} P_M (1 + \rho c/Z_M)$$

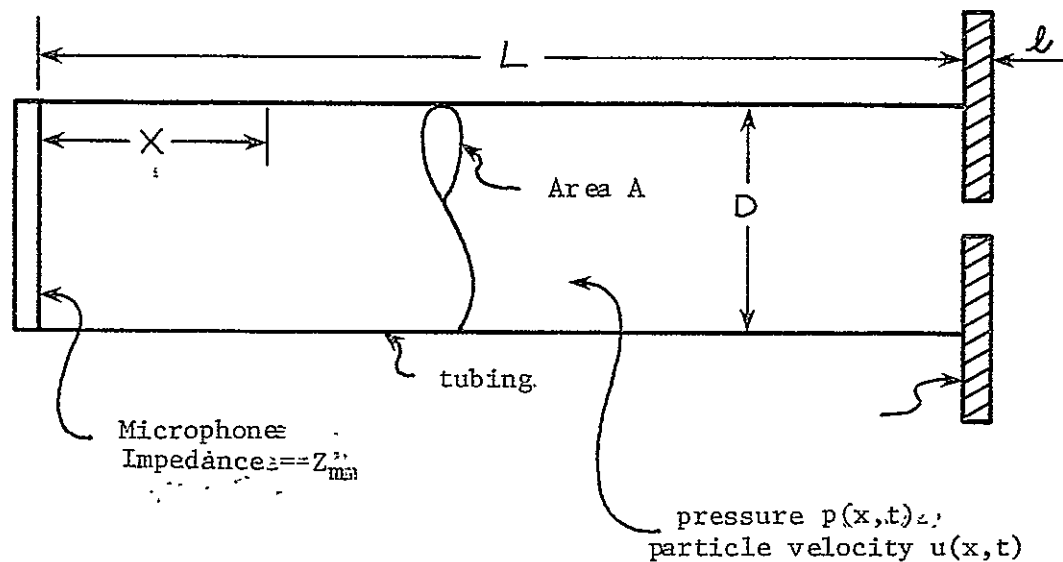
$$P_R = \frac{1}{2} P_M (1 - \rho c/Z_M)$$

Eliminating P_L and P_R

$$p(x,t) = \frac{P_M}{2} \left\{ (1 - \rho c/Z_M) e^{-ikx} + (1 + \rho c/Z_M) e^{ikx} \right\} e^{i\omega t}$$

$$= P_M \left\{ \cos kx + \frac{i\rho c}{Z_M} \sin kx \right\} e^{i\omega t}$$

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Additional definitions of terms:

a =Total area of pressure sensing holes

$\dot{X}$ =Volume flow rate

d =Diameter of individual hole

d^1 =Effective diameter of a group of small holes

Figure 4.1.1 Model for Analysis of Pressure Probes

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$$\begin{aligned} \dot{X}(x,t) = u(x,t) A &= \frac{P_M A}{2\rho c} \left\{ \left(1 - \frac{\rho c}{Z_M}\right) e^{-ikx} - \left(1 + \frac{\rho c}{Z_M}\right) e^{ikx} \right\} e^{i\omega t} \\ &= \frac{-P_M A}{\rho c} \left\{ i \sin kx + \frac{\rho c}{Z_M} \cos kx \right\} e^{i\omega t} \end{aligned}$$

The k in these equations is complex to account for decay of the signal in the plastic tubing.

$$k = k' - i\alpha$$

where

$$\begin{aligned} k' &= \frac{\omega}{c \left[1 - \frac{1}{D} \frac{2v}{\omega} \right]} \\ \alpha &= \frac{1}{DC} \sqrt{2 v \omega} \end{aligned}$$

Figure 4.1.2 shows the pulsating slug of air contained within the one small pressure sensing hole of diameter d . The viscous pressure term, P_{visc} , is derived as follows, with the aid of Figure 4.1.3.

$$P_{\text{visc}} = \frac{-2\pi\eta\mu\ell}{\pi\eta^2} \frac{dv}{d\eta}$$

where v is the velocity at a distance from the centerline, and μ is the viscosity. Assuming a parabolic velocity distribution

$$v = 2 \dot{s} \left[1 - \left(\frac{2}{d} \right)^2 \right]$$

$$P_{\text{visc}} = \frac{32\mu\ell\dot{s}}{d^2}$$

Assuming several holes of equal diameter, with total area, a

$$P_{\text{visc}} = \frac{32\mu\dot{X}(L,t)}{ad^2}$$

where

$$\dot{s} = \dot{X}(L,t)/a$$

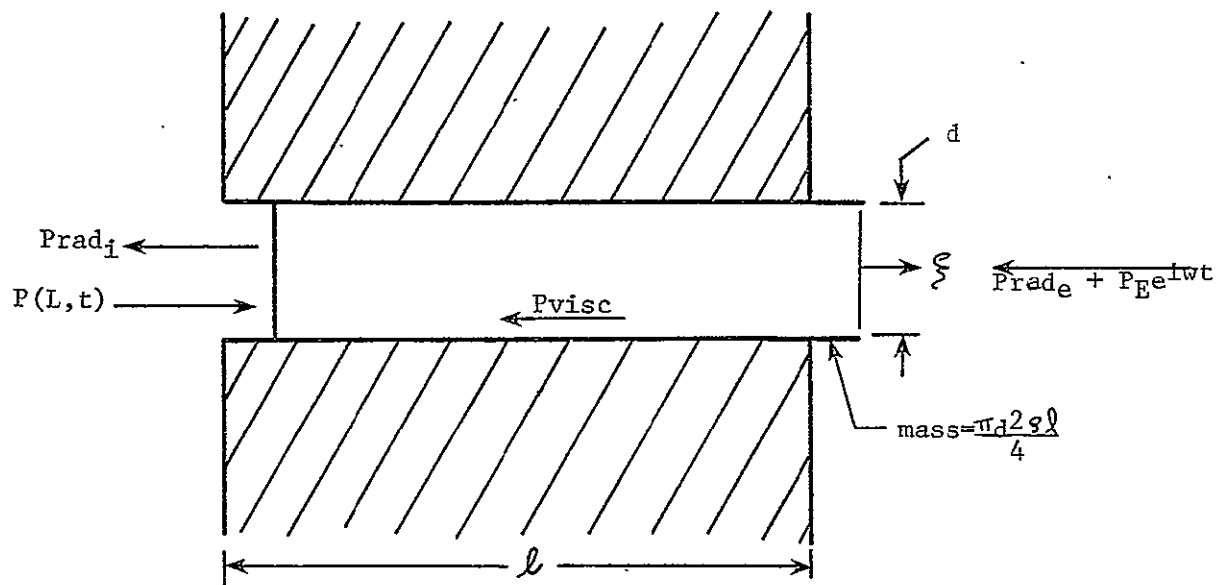


Figure 4.1.2 Pulsating Air Slug

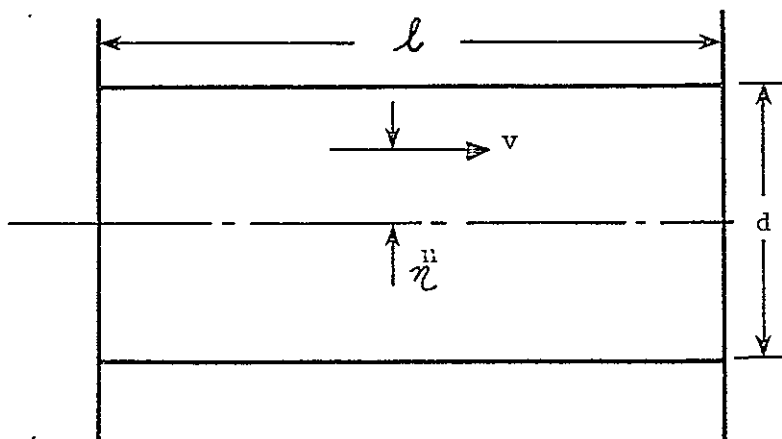


Figure 4.1.3 Equivalent Pulsating Sphere

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Since a parabolic velocity distribution was assumed, a multiplication factor, MF, must also be used to compensate for any effects due to a different profile. It should be noted that the assumption of a parabolic profile is unrealistic for such short holes as are used here. The final viscous pressure term is

$$P_{\text{visc}} = \frac{32 \text{ MF} \mu \dot{X}(L,t)}{ad^2}$$

The radiation pressure is derived for two cases. In case (1), a surface pressure port consists of a group of holes on a flat surface, as shown in Figure 4.1.4. This pressure port is treated as a piston inset in a infinite plane. In case (2), the holes in a static pressure probe are assumed to simulate a pulsating sphere, as shown in Figure 4.1.5.

Case (1) Equivalent Piston

The group of holes shown in Figure 4.1.4 has a combined area of a , and approximates a piston of diameter d' . Then

$$P_{\text{rad}} = u_p \rho c \left[\frac{k^2 d'^2}{8} + \frac{i4kd'}{3\pi} \right]$$

where

$$u_p = \frac{4\dot{X}(L,t)}{\pi d'^2}$$

therefore

$$P_{\text{rad}} = \frac{\rho c \dot{X}(L,t)}{\pi d'^2} \left[\frac{k^2 d'^2}{2} + \frac{i16kd'}{3\pi} \right]$$

$\uparrow \qquad \qquad \uparrow$
 radiation effective mass

The expression used for P_{rad_e} , the external radiation pressure, is identical to the above expression. The expression used for P_{rad_i} , the

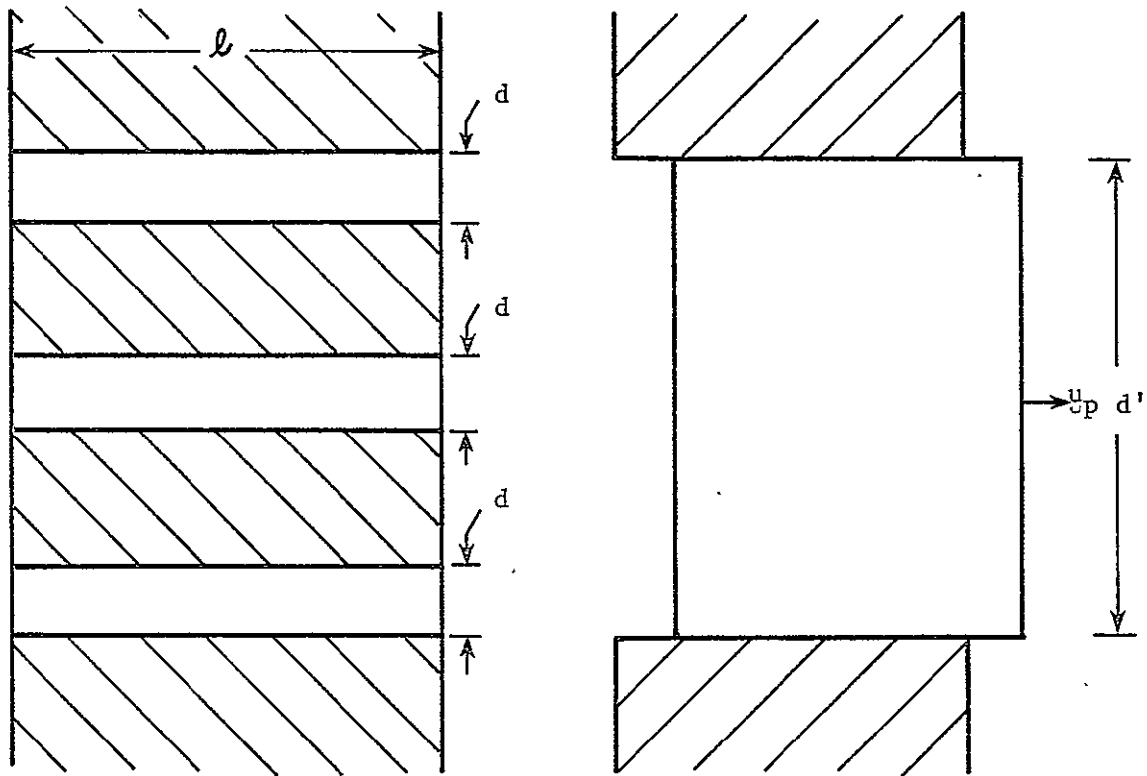


Figure 4.1.4 Equivalent Piston

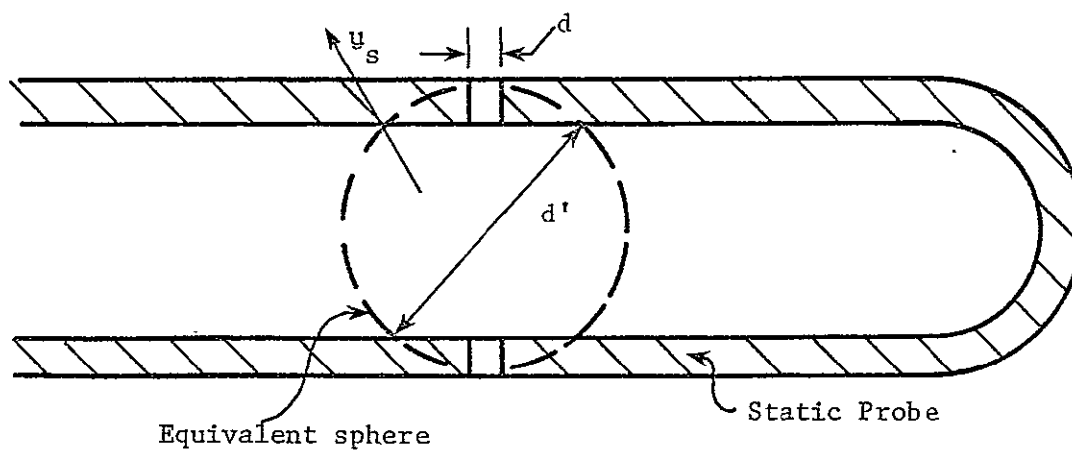


Figure 4.1.5 Equivalent Pulsating Sphere

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internal radiation pressure, is assumed to consist only of the effective mass term.

The final solution for the transfer function is obtained by combining all of the forces acting on a single slug of air, as shown in Figure 4.1.2.

$$\frac{\pi d^2 \rho \ell \dot{s}}{4} = \frac{\pi d^2}{4} [p(L,t) - P_{\text{visc}} - P_{\text{RAD}_e} - P_{\text{RAD}_i} - P_E e^{i\omega t}]$$

then with

$$\dot{s} = \dot{X}(L,t)/a$$

$$\frac{\rho \ell \ddot{X}(L,t)}{a} = \left[p(L,t) - P_{\text{visc}} - P_{\text{rad}_e} - P_{\text{rad}_i} - P_E e^{i\omega t} \right]$$

so that

$$\frac{i\omega \rho \ell \dot{X}(L,t)}{a} = p(L,t) - \left\{ \frac{\rho c k^2}{2\pi} + \frac{i32\rho c k}{3\pi^2 d'} + \frac{32MF\mu\ell}{ad^2} \right\} \dot{X}(L,t) - P_E e^{i\omega t}$$

and on substitution for $\dot{X}(L,t)$ and $p(L,t)$

$$T.F. = P_M/P_E$$

$$= \left[\left\{ \cos kL + \frac{i\rho c}{Z_M} \sin kL \right\} - \left\{ \left(\frac{A\ell}{a} + \frac{32A}{3\pi^2 d'} \right) k - \frac{iAk^2}{2\pi} \right\} \right]$$

$$\frac{i32MFVA\ell}{ad^2c} \left\{ \sin kL - \frac{i\rho c}{Z_M} \cos kL \right\}]^{-1}$$

Case (2) Equivalent Sphere

The group of holes shown in Figure 4.1.5 has an effective area of a , but it approximates a pulsating sphere of diameter d' . It is intended to represent a static pressure probe. Then

$$P_{\text{rad}} = \rho c u_s \left[\frac{k^2 d'^2/4 + ikd'/2}{1 + k^2 d'^2/4} \right]$$

$$\approx \frac{\rho c \dot{X}(L,t)}{d'^2} \left[\underbrace{\frac{k^2 d'^2}{4}}_{\text{radiation}} + \underbrace{\frac{ikd'}{2}}_{\text{effective mass}} \right]$$

where

$$u_s = \dot{X}(L, t) / \pi d^2$$

As before, P_{rad_e} is taken as above, while the P_{rad_i} term is neglected.

The final solution is obtained as before

$$\begin{aligned} T.F. &= P_M / P_E \\ &= \left[\left\{ \cos kL + \frac{i\rho c}{Z_M} \sin kL \right\} - \left\{ \left(\frac{A\ell}{a} + \frac{A}{2\pi d^2} \right) k - \frac{iAk^2}{4\pi} \right. \right. \\ &\quad \left. \left. - \frac{32iMFVA}{ad^2c} \right\} \left\{ \sin kL - \frac{i\rho c}{Z_M} \cos kL \right\} \right]^{-1} \end{aligned}$$

Assuming that k' is much greater than α , so that k is almost a real quantity, and that the microphone impedance, Z_M , is very high, the two transfer functions given above will have peaks and valleys corresponding to the zeros of $\cos kL$ and $\sin kL$. If the second inner bracketted term is small, as will be the case if the holes are large [the tube is effectively open-ended], then the transfer function will peak at the zeros of $\cos kL$. If this term is large, corresponding to small holes, the transfer function will peak at the zeros of $\sin kL$, as would be the case with a closed ended tube. If the external pressure were sufficiently large, the total head loss would become predominant. This would create apparent noise, and it would make the system nonlinear, so that the concept of a transfer function would be an approximation. [The formulae for radiation pressure and for attenuation in a tube, were taken from Kinsler and Frey^[20].]

4.2 Evaluation of Pressure Sensors

Pitot Probes vs. Static Probes

Fluctuating pressures were measured, 10 cm downstream on the jet

axes, to compare the CROSSPECT and 1/3 octave spectra of a pitot probe and a static probe [Figures 4.2.1-4.2.3]. In both cases, the probes were connected to a 1/8 in. (3.175 mm) B&K microphone through 149 cm. of plastic tubing. Comparison of these spectra indicates that the pitot probe measures higher overall pressure levels with a larger low frequency content. The static probe, having a lower signal to noise ratio, shows a more pronounced Strouhal number peaking.

It was found, that when two pitot probes were used simultaneously, the cross-correlation values decreased rapidly when radial probe separation was increased. When static probes were used, the cross-correlation values remained much higher through identical probe separations. Table 1 shows the comparison of maximum correlation coefficients between the pitot and static probes, where X is the axial location downstream from the jet and Y is the radial location from the jet centerline.

Table 1

$\frac{X}{D_j}$	$\frac{Y}{D_j}$	Pitot Probe Maximum <u>Correlation Coefficient</u>	Static Probe Maximum <u>Correlation Coefficient</u>
2	.142	.684	.849
2	.25	.511	.688
2	.50	.081	.383
2	.75	.012	.374
2	1.00	.006	.423
4	.142	.674	.877
4	.25	.201	.694
4	.50	.068	.485
4	.75	.018	.403
4	1.00	.001	.356

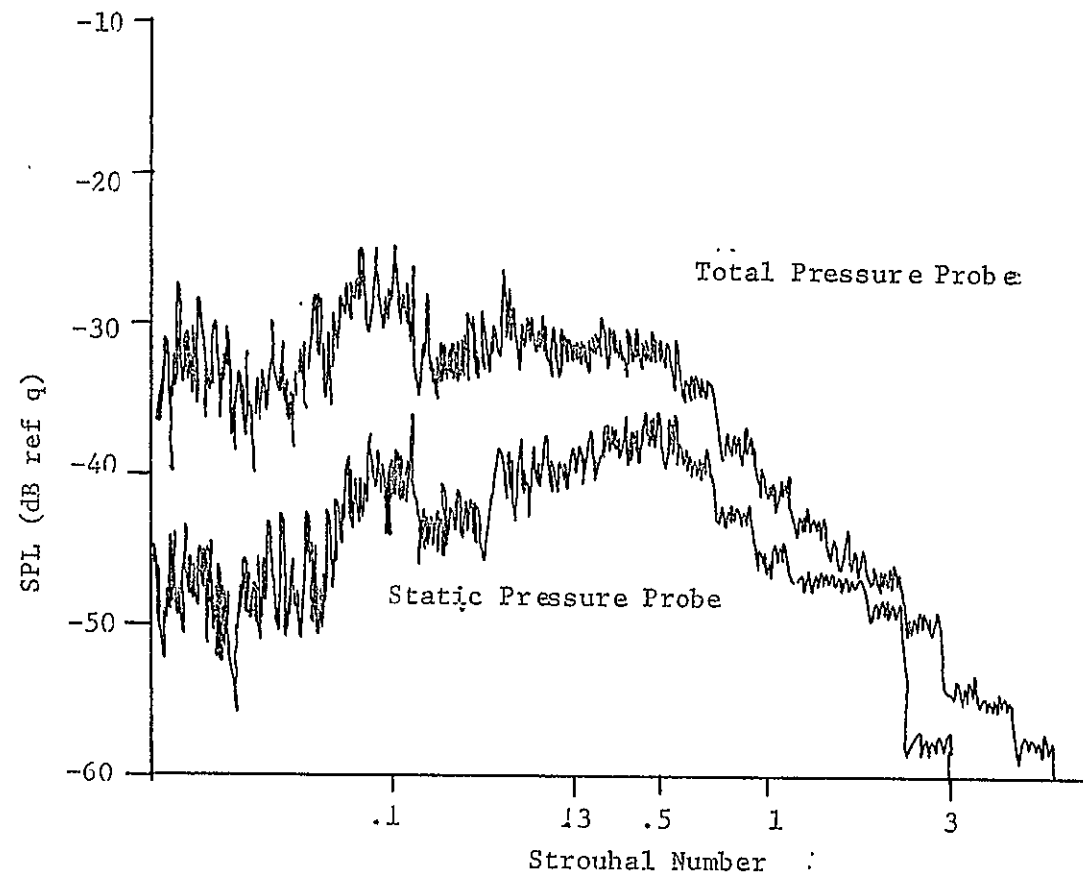


Figure 4.2.1 1/3 Octave Spectra of Total Pressure Probe
and Static Pressure Probe

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STATIC PRESSURE PROBE - RUN NO. 15

CHANNEL 1. -X=10.0 CM. Y=0.0 CM.

FULL LINE/AUTO SPECTRUM, RMS. DB.= -52.78

DASH LINE/NOISE LEVEL, RMS. DB.= -75.13

QREF= 152.00 DB./REF. FREQ. IN HZ.= 1120.00

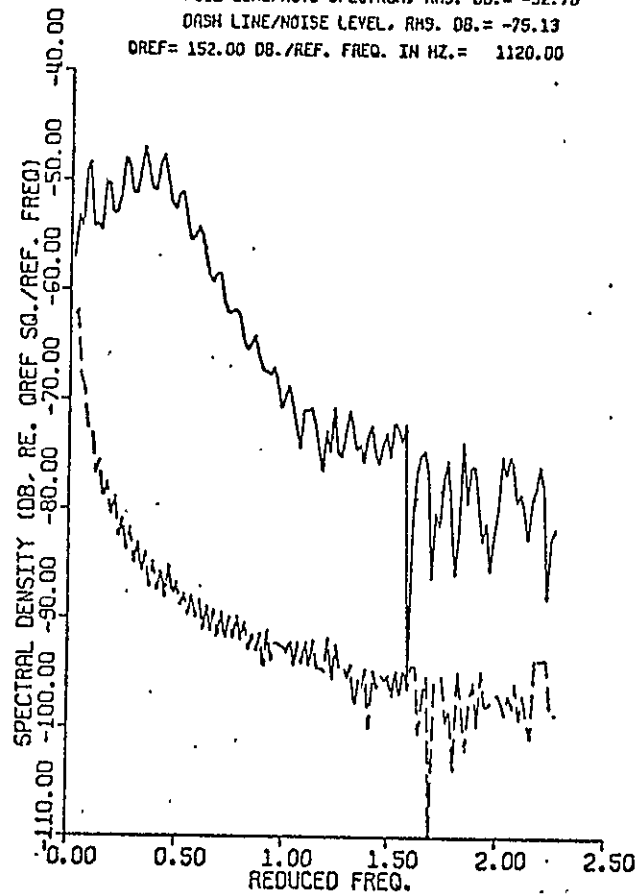


Figure 4.2.2 - Power Spectra of Static Pressure Probe

TOTAL PRESSURE PROBE - RUN NO. 15

CHANNEL 1. -X=10.0 CM. Y=0.0 CM.

FULL LINE/AUTO SPECTRUM, RMS. DB.= -42.92

DASH LINE/NOISE LEVEL, RMS. DB.= -76.61

QREF= 152.00 DB./REF. FREQ. IN HZ.= 1120.00

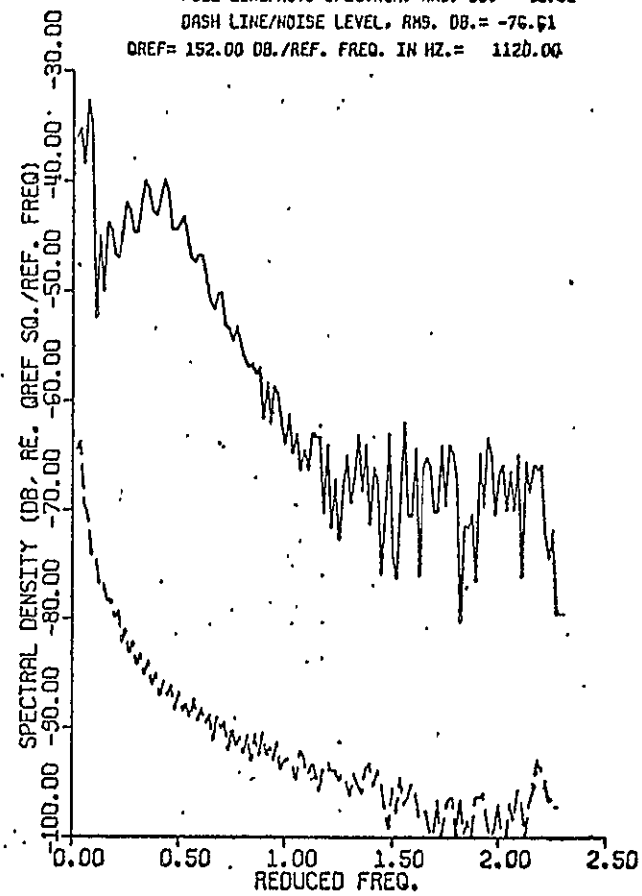


Figure 4.2.3 - Power Spectra of Total Pressure Probe

The apparent reason for this is, pitot pressure is dependent on the cross-components of velocity fluctuations and vortex front passages. In the regions of the sheared annulus and vortex ring breakup, the flow becomes extremely complex and irregular, making it advantageous to use the static probes which depend only on static pressure fluctuations. The pitot probes were found to be useful in calculating convection velocities because of their higher signal to noise ratio.

Static Probes vs. Microphone

The transfer function of one of the original static probes with four .01 in (.254 mm) holes was found experimentally by positioning it outside the direct flow, next to an exposed microphone, 2 diameters downstream of the jet exit and 1 diameter radially outward from the jets axis. Channel 2 input into the correlator was from the exposed microphone, Channel 1 input was from a static probe through 100 cm plastic tubing to another microphone. The transfer function [Figure 4.2.4] indicates that the probe and tubing system not only give the expected peaks and valleys, but also causes an overall attenuation of the measured pressure. To correct for this attenuation, one of the probes was modified by doubling the diameters of the pressure sensing holes to .02 in [.508 mm] and the experimental procedure was repeated. The transfer function for this new probe [Figure 4.2.5] no longer shows this overall attenuation. The Strouhal number range of the transfer function is limited because of the weak effect of the jet flow in the measured region.

Surface Probes vs. Microphone.

A special plate [Figure 4.2.6] was designed to make experimental

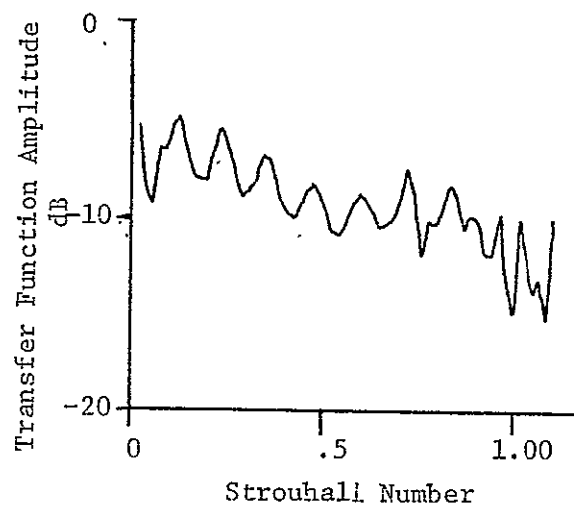
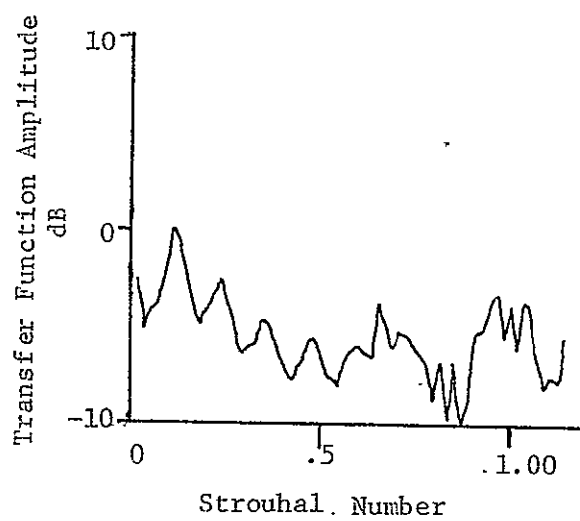


Figure 4.2.4 Transfer Function of Static Probe



4.2.5 Transfer Function of New Static Probe

comparisons between a surface probe and a 1/8 in [3.175 mm] flush mounted microphone. The plate was inserted into the flow at an inclination angle, β , of 30° , 9.0 cm downstream of the jet exit, and all pressure sensors were symmetrically located 3/8 in [9.525 mm] from jet axis. Comparisons were made by computing transfer functions using the CROSSPECT program in the following cases:

Tubing Length

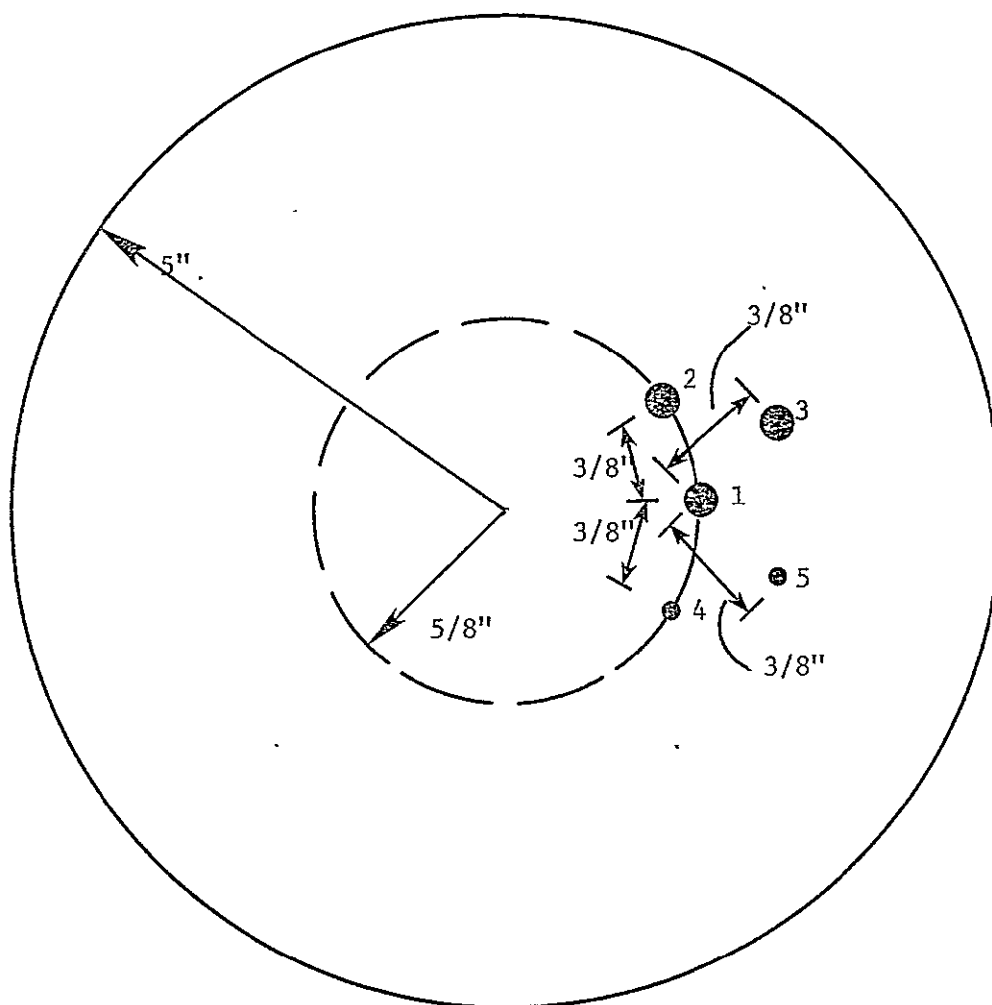
The effect of different tubing lengths was investigated. Channel 2 input into the correlator was from the flush mounted microphone and Channel 1 input was from a .02 in [.508 mm] diameter pressure port through plastic tubing of different lengths to another microphone. Figures 4.2.7-4.2.9 show the transfer functions for tubing lengths of 0.5 m, 1.0 m, and 2.0 m, respectively. The tubing length comparison shows how the peaks of the transfer function vary. As expected, the shorter the tubing the greater the separation between resonance peaks, the longer the tubing the closer the peaks are together.

Pressure Port Hole Diameter

The effect of different pressure port diameters was also investigated. Channel 2 input into the correlator was again the flush mounted mike, Channel 1 input was from different diameter pressure ports through 1.0 m long plastic tubing to the other microphone. Figures 4.2.10-4.2.12 show the transfer functions for pressure port diameters of .01 in [.254 mm], .02 in [.508 mm], and .04 in [1.016 mm], respectively.

The effect of pressure port diameter is in accordance with the theoretical predictions. At diameter equal to .01 [.254 mm] the transfer

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- Port #1 - Flush Mounted Mike
- 2 - Kulite Probe
- 3 - 0.004" Diameter Pressure Port
- 4 - 0.02" Diameter Pressure Port
- 5 - 0.01" Diameter Pressure Port

Figure 4.2.6 Special Impingement Plate

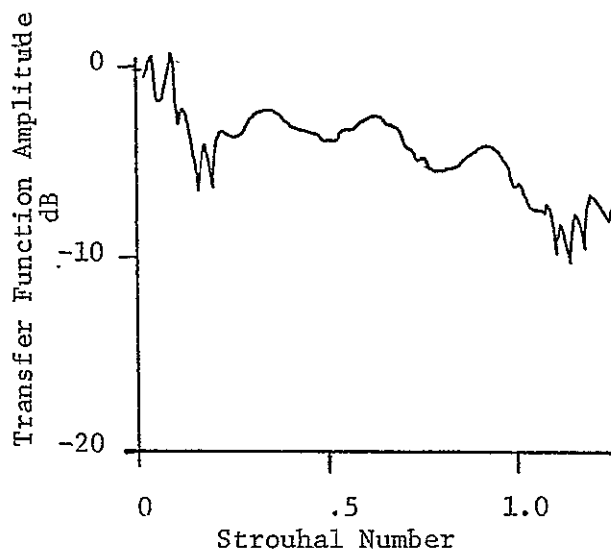


Figure 4.2.7 Transfer Function - Tubing length = 0.5 m

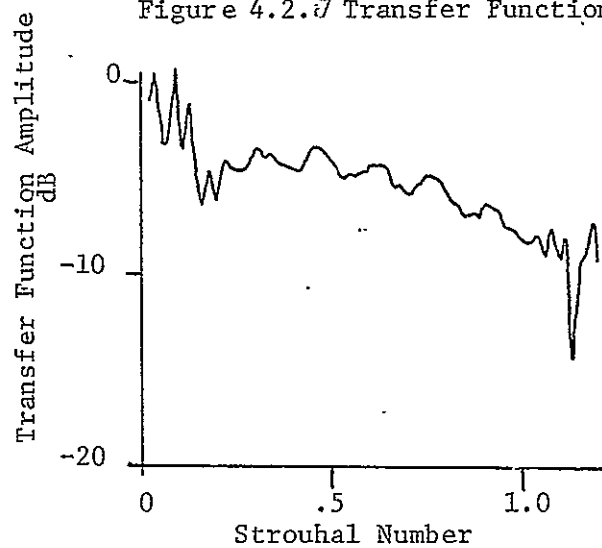


Figure 4.2.8 Transfer - Tubing length = 1.0 m

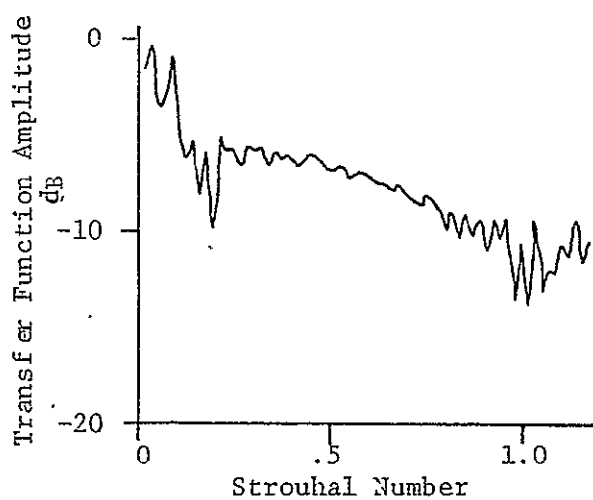


Figure 4.2.9 Transfer Function - Tubing length = 2.0 m

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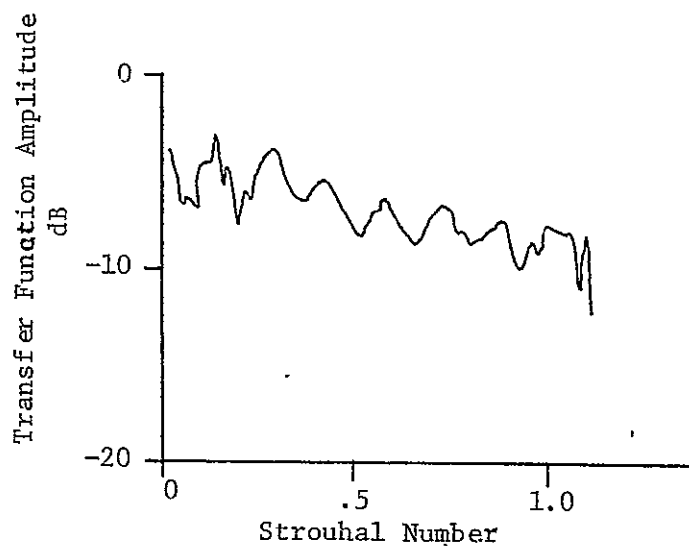


Figure 4.2.10 Transfer Function - Diameter = .01 in

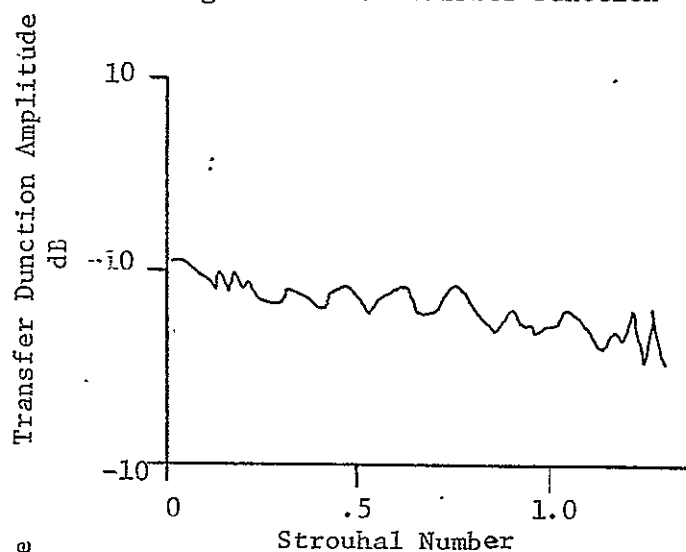


Figure 4.2.11 Transfer Function - Diameter = .02 in

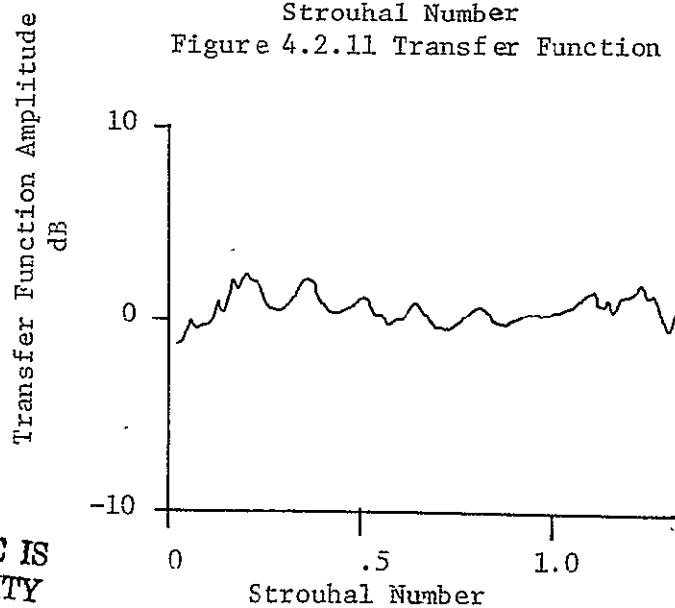


Figure 4.2.12 Transfer Function - Diameter = .04 in

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function follows an inverse sine function [same as a closed-closed system]. At a diameter of .02 in [.508 mm] the peaks have shifted over and now are a combination of inverse sine plus cosine. At a diameter of 0.4 in [1.016 mm] the peaks have shifted over to an inverse cosine function [same as an open-closed system].

Kulite Transducer

A comparison was made between the flush mounted microphone [channel 2] and a Kulite transducer [channel 1]. The transfer function [Figure 4.2.13] indicates that these two pressure sensors measure the same pressure fluctuations. The signal to noise ratio from the homemade amplifiers were low making meaningful data from the Kulites hard to obtain.

Tubing Material

The effect of different tubing material connecting a surface probe to a 1/8 in [3.175 mm] B&K microphone was investigated by examining the transfer function between a 1.0 in long plastic tube connected to a .02 in [.508 mm] diameter pressure port and a 1.0 m long stainless tube connected to an identical pressure port. The transfer function [Figure 4.2.14] is approximately equal to 0.0 dB throughout the frequency range, indicating that tubing material does not effect the transfer function of the tubing system.

4.3 Calculated Transfer Functions

The transfer functions were calculated for both a static probe, with .02 inch diameter holes, and a .04 inch [1.016 mm] surface probe using the equations derived in Section 4.1. Multiplication factors, ME , [defined in

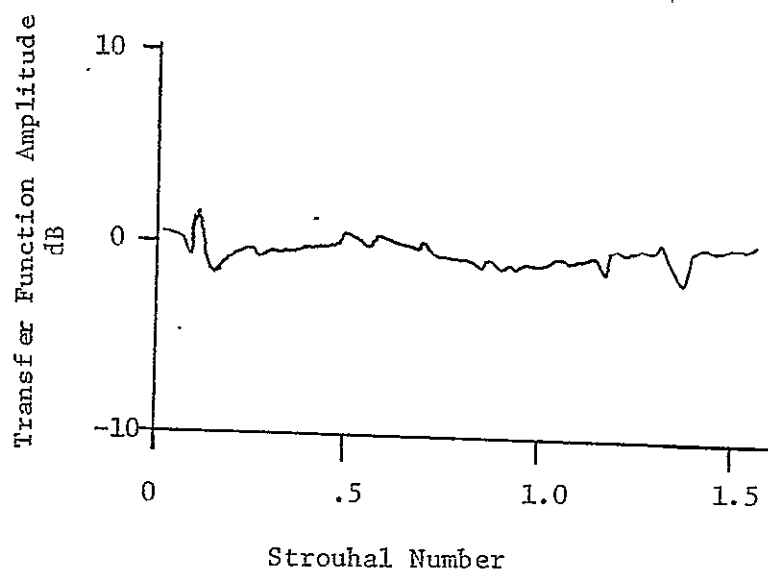


Figure 4.2.13 - Comparison between 1/8 microphone and Kulite Pressure Transducer

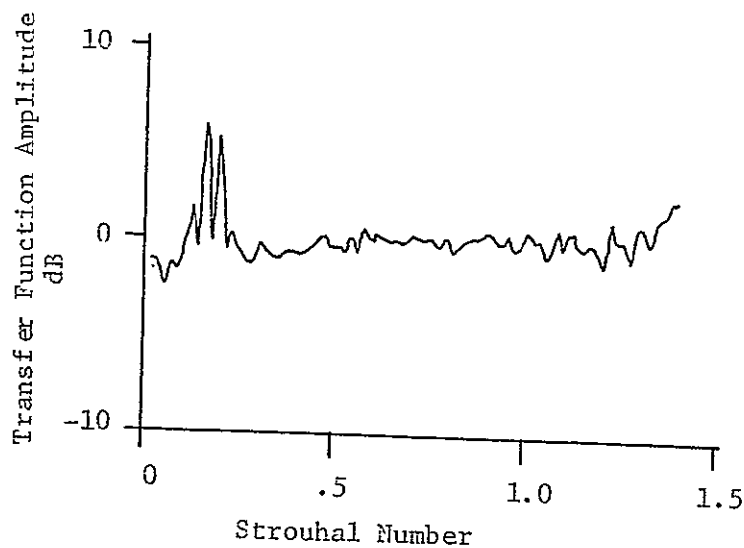


Figure 4.2.14 - Comparison between Stainless Steel Tubing, and Plastic Tubing

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Section 4.1] of 150 for the static probe and 31 for the pressure port were found to give the best representations of the transfer functions found experimentally [Section 4.2].

The phase lag and transfer function amplitude of the calculated transfer function for the static probe is shown in Figure 4.3.1. Figures 4.3.2 and 4.3.3 show the spectral density, phase lag and transfer function amplitude for the static probe, calculated by CROSSPECT after the calculated transfer function has been inserted to compensate for the tubing system transfer function. The phase lag and transfer function amplitude of the calculated transfer function for the pressure port is shown in Figure 4.3.4, Figures 4.3.5 and 4.3.6 show the compensated spectral density, phase lag and transfer function amplitude for the pressure port.

The calculated transfer functions do improve the spectral density and transfer function amplitude. However, the compensation does not completely erase the amplitudes caused by the tubing system and does not correct for the phase shifting that occurs. More work is needed to develop more accurate transfer functions. Such things as area changes in the probes are not accounted for and a more precise method of calculating tubing length is needed. These transfer functions do show the correct tendencies and are helpful in reducing the amplitude peaks.

TRANSFER FUNCTION - RUN NO. 3

PHASE ANGLE AND TR. FUNCTION AMP.

QREF= 151.84 DB./REF. FREQ. IN HZ.= 1097.16

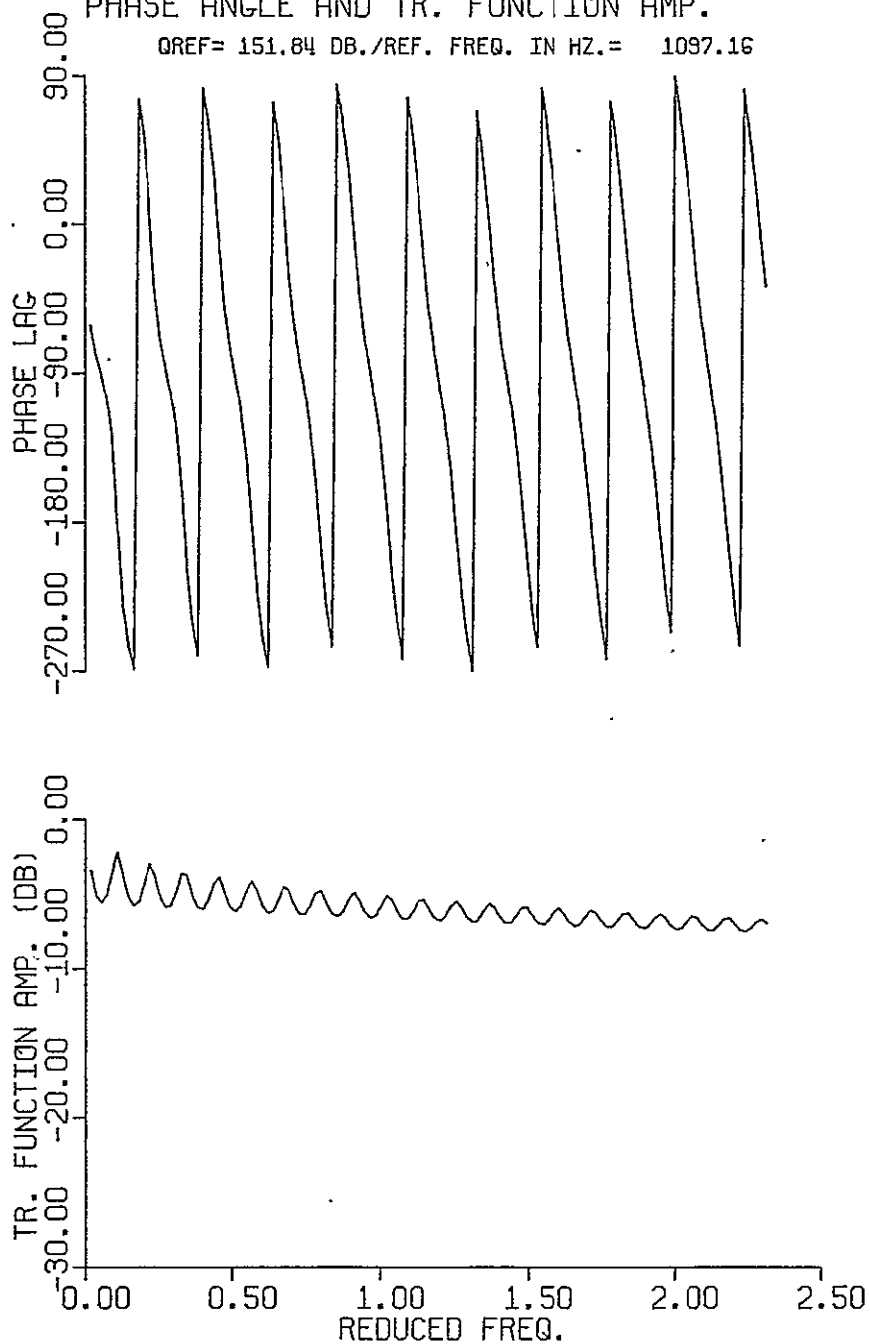


Figure 4.3.1 Calculated Transfer Function Amplitude
and Phase Lag for Statics Pressure Probe

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CORRECTED TF-STATIC2 VS. MIKE - RUN NO. 38

CHANNEL 1. -STATIC2 PROBE

FULL LINE/AUTO SPECTRUM, RMS. DB. = -50.70

DASH LINE/NOISE LEVEL, RMS. DB. = -55.11

QREF = 151.84 DB./REF. FREQ. IN HZ. = 1097.16

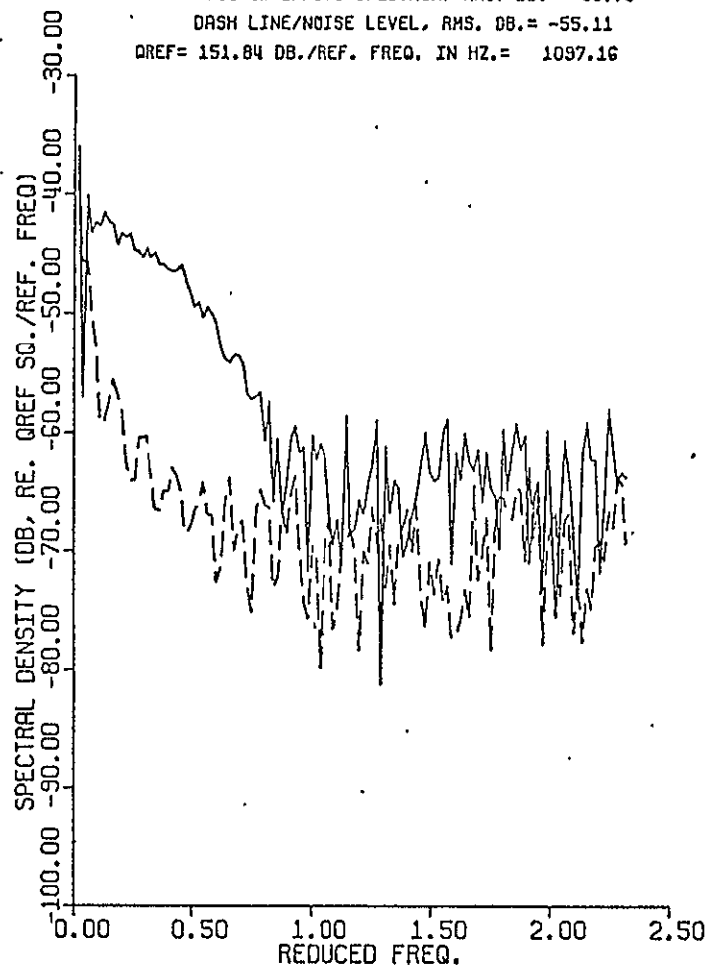


Figure 4.3.2 Compensated Spectral Density for Static Pressure Probe

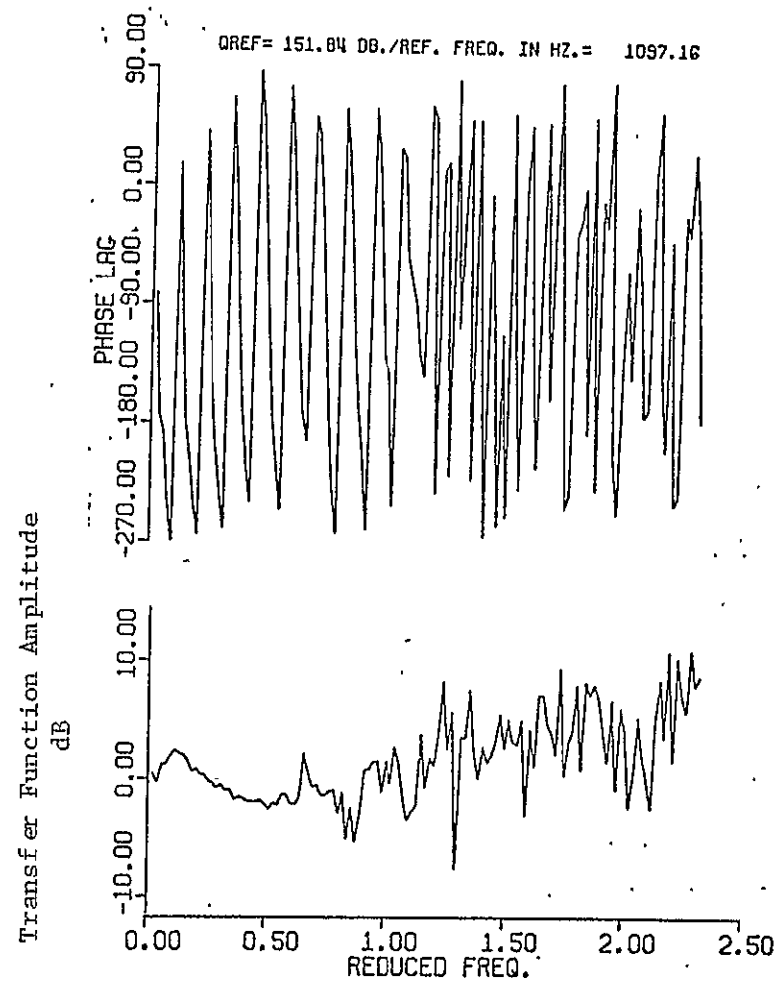


Figure 4.3.3 Compensated Phase lag and Transfer Function Amplitude for Static Pressure Probe

TRFCT-FLAT PLATE - RUN NO. 31

PHASE ANGLE AND TR. FUNCTION AMP.

QREF= 152.00 DB./REF. FREQ. IN HZ.= 1116.00

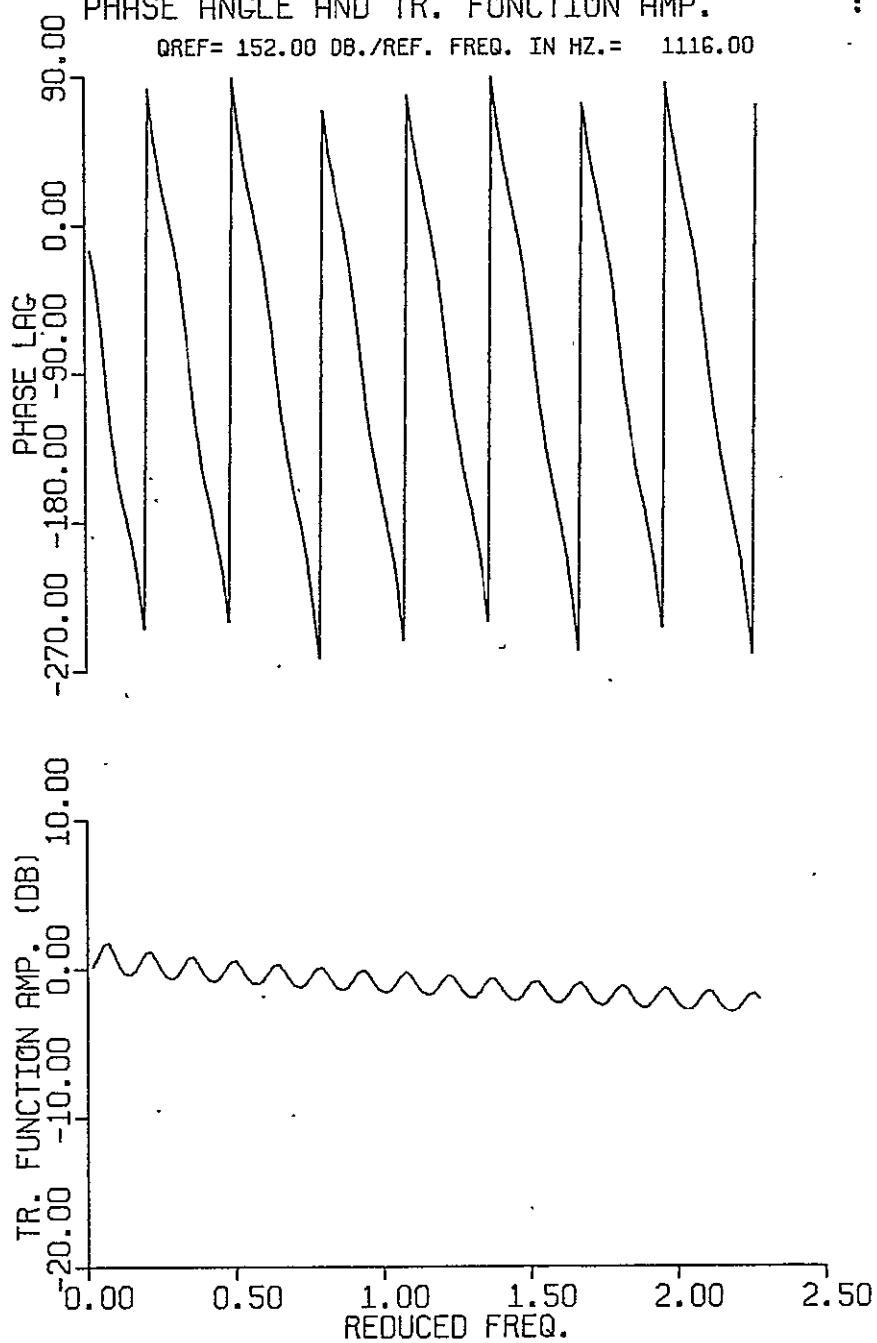


Figure 4.3.4 Calculated Transfer Function Amplitude and Phase Lag for Pressure Port

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TRFCT CHECK-PLATE;D=.04 IN. - RUN NO. 31

CHANNEL 1. -PRESSURE PORT

FULL LINE/AUTO SPECTRUM, RMS. DB.= -31.03

DASH LINE/NOISE LEVEL, RMS. DB.= -68.03

DREF= 152.00 DB./REF. FREQ. IN HZ.= 1116.00

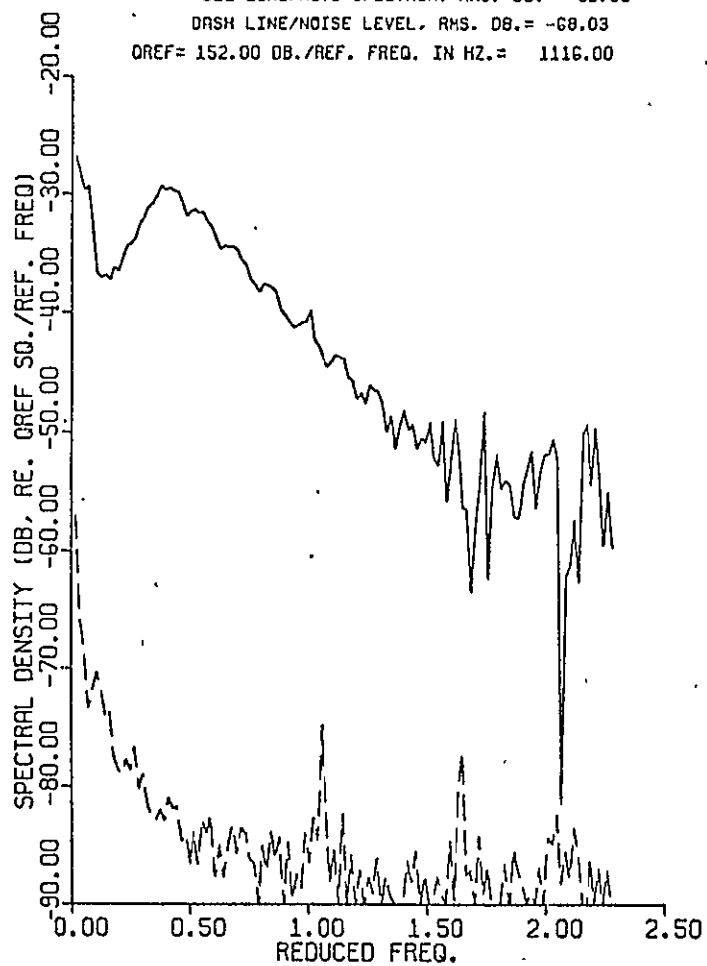


Figure 4.3.5 Compensated Spectral Density for Pressure Port

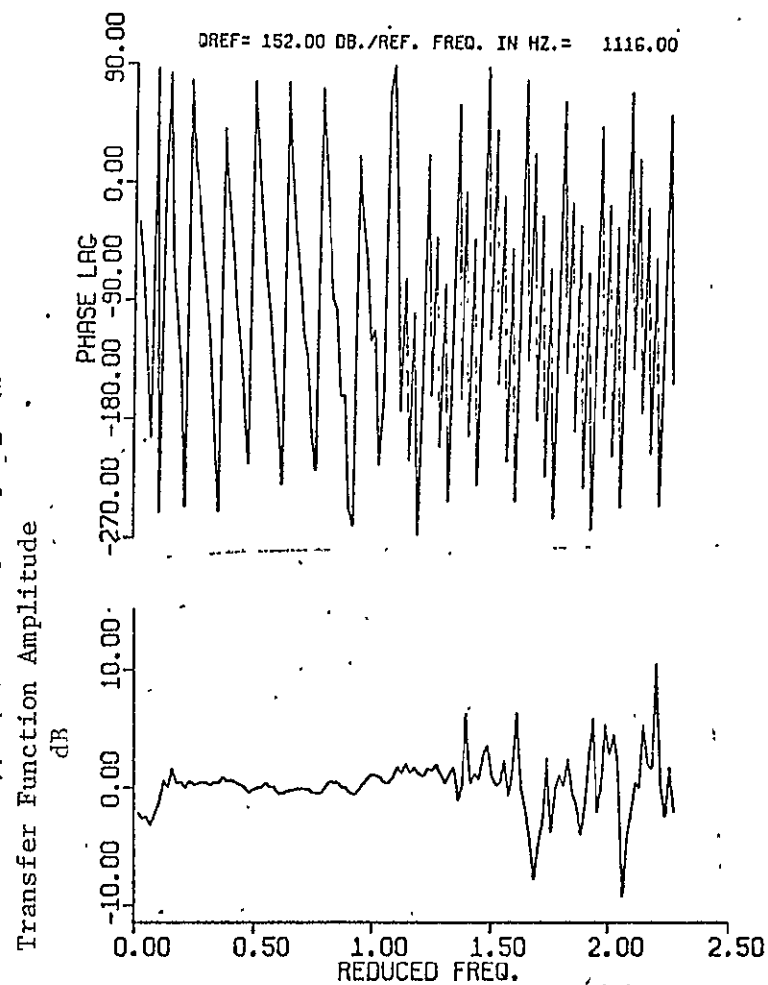


Figure 4.3.6 Compensated Phase lag and Transfer Function for Pressure Port

Chapter 5

EXPERIMENTAL RESULTS

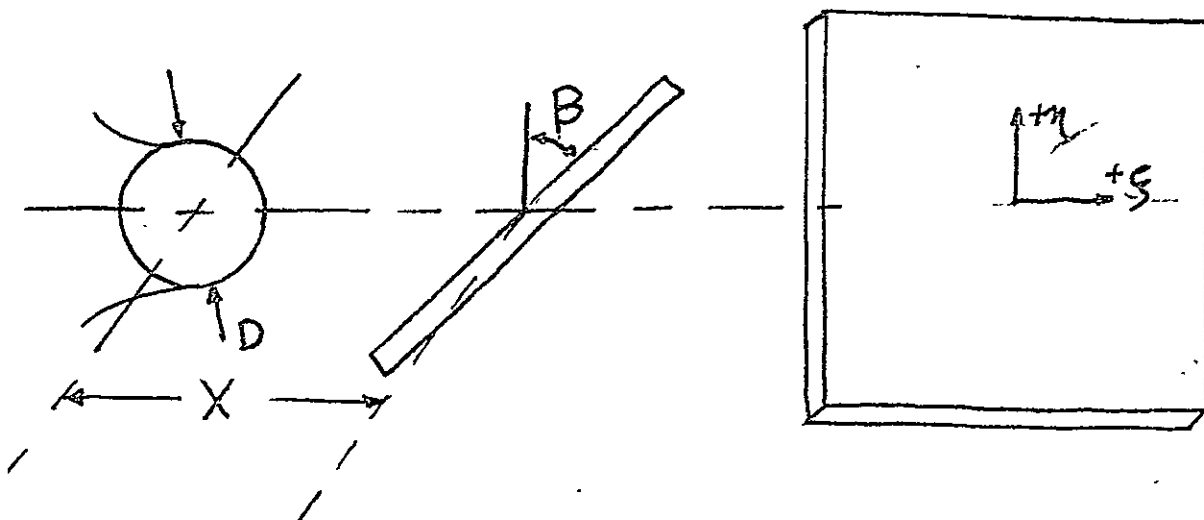
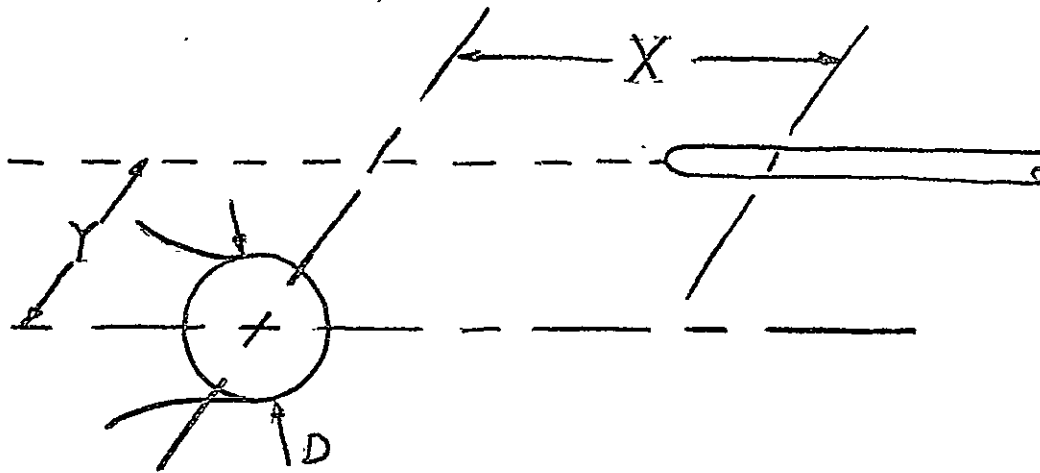
This chapter deals with experimental investigations into the fluctuating pressures behind a cold round jet, both with the jet free, and with the jet impinging on a flat plate. In all the data presented, the jet exit diameter is 3.17 cm, with exit velocity of approximately 35 m/s, giving a jet exit Reynolds number of about 74,000.

Figure 5.0.1 indicates the coordinate systems used in this investigation. The X coordinate gives the downstream location from the jet exit and Y is the location radially outward from the jet centerline. For measurements on the flat plate, η is the coordinate along the projected jet centerline and ξ is the coordinate perpendicular to this centerline. β is the angle of impingement.

5.0 Free Jet - P_{rms} and Mean Dynamic Pressure Levels

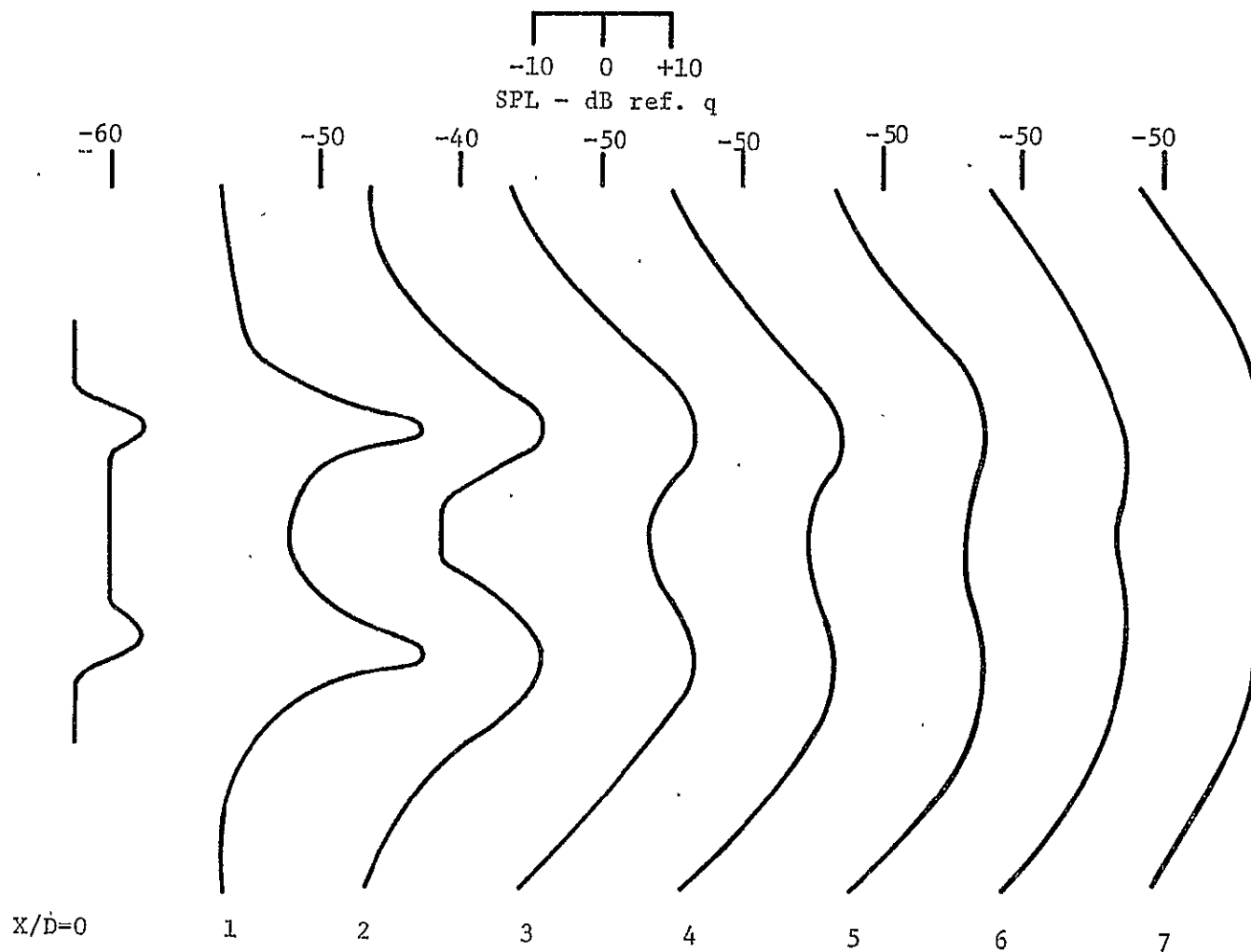
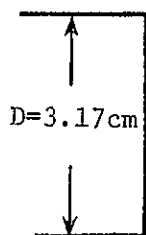
Fluctuating "static" and mean dynamic pressure profiles were taken from zero to eight diameters downstream. The static pressure probes described in Chapter 3 were used with four pressure sensing holes .02 inches in diameter. These profiles are shown in Figures 5.0.2 and 5.0.3. In these figures, the levels are given in decibel form referenced to the jet exit dynamic pressure, q .

The fluctuating pressure levels are lowest in the potential core region, indicating low turbulence levels. The levels are higher behind the lip of the jet due to the increased turbulence levels associated with the sheared annulus. The relative levels in the potential core

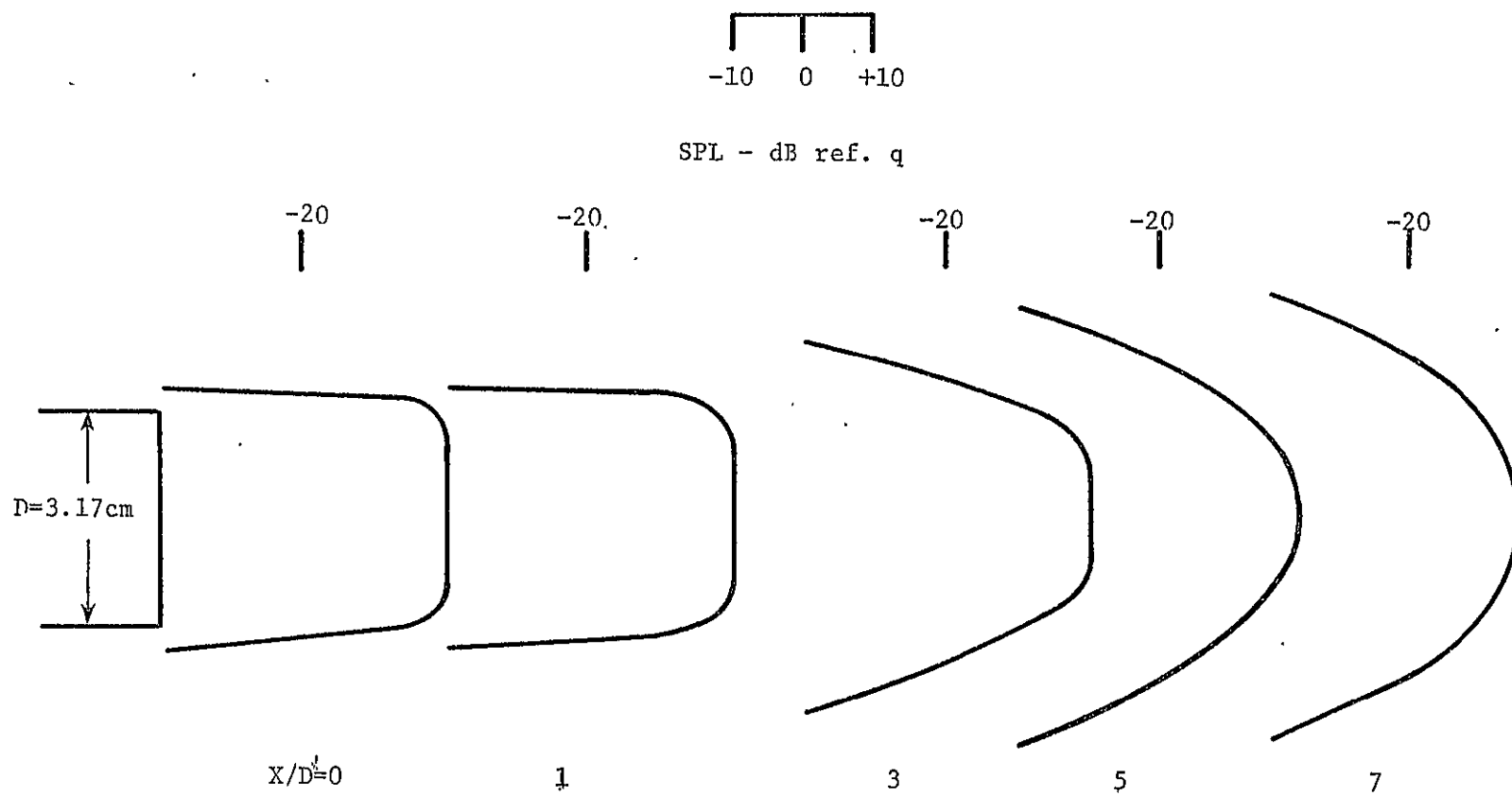


5.0.1 Definition of Coordinate Systems

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5.0.2 Free Jet "Static" Fluctuating Pressure Level Profiles



5.0.3 Free Jet Mean Dynamic Pressure Profiles

increase as the downstream distance from the jet exit is increased, eventually approaching a normal type distribution.

The mean dynamic pressure profiles indicate that the centerline level remains fairly constant throughout the potential core region. These profiles show the downstream spreading of the jet and indicate how the centerline pressure begins to decrease beyond the potential core region.

5.1 Free Jet - 1/3 Octave Spectra

Figures 5.1.1 - 5.1.7 show the 1/3 octave fluctuating "static" pressure levels measured behind the free jet using the static pressure probes. The fluctuating levels are given in decibel form referenced to q and the frequency scale has been converted to Strouhal number form, $St. No. = fD/U_j$. In each of the figures, five spectra are shown corresponding to probe locations varying from the jet centerline radially outwards to one jet diameter. Each figure corresponds to a different location downstream from the jet exit, the locations illustrated are between 2 and 10 jet diameters.

The spectra corresponding to locations of 2, 3 and 4 jet diameters downstream indicate a Strouhal number dependence, as predicted by the vortex model of a free jet. At a downstream location of 2 jet diameters, the spectra peak at a Strouhal number of 0.3 to 0.5. This peak is present in all the spectra, however, at a location of $Y/D=0.5$ the spectrum is more uniform because of the increased fluctuating pressure levels encountered in the sheared annulus region of the jet. The peak again is apparent outside of this sheared annulus region. The presence of this Strouhal peak becomes less pronounced with increased distance

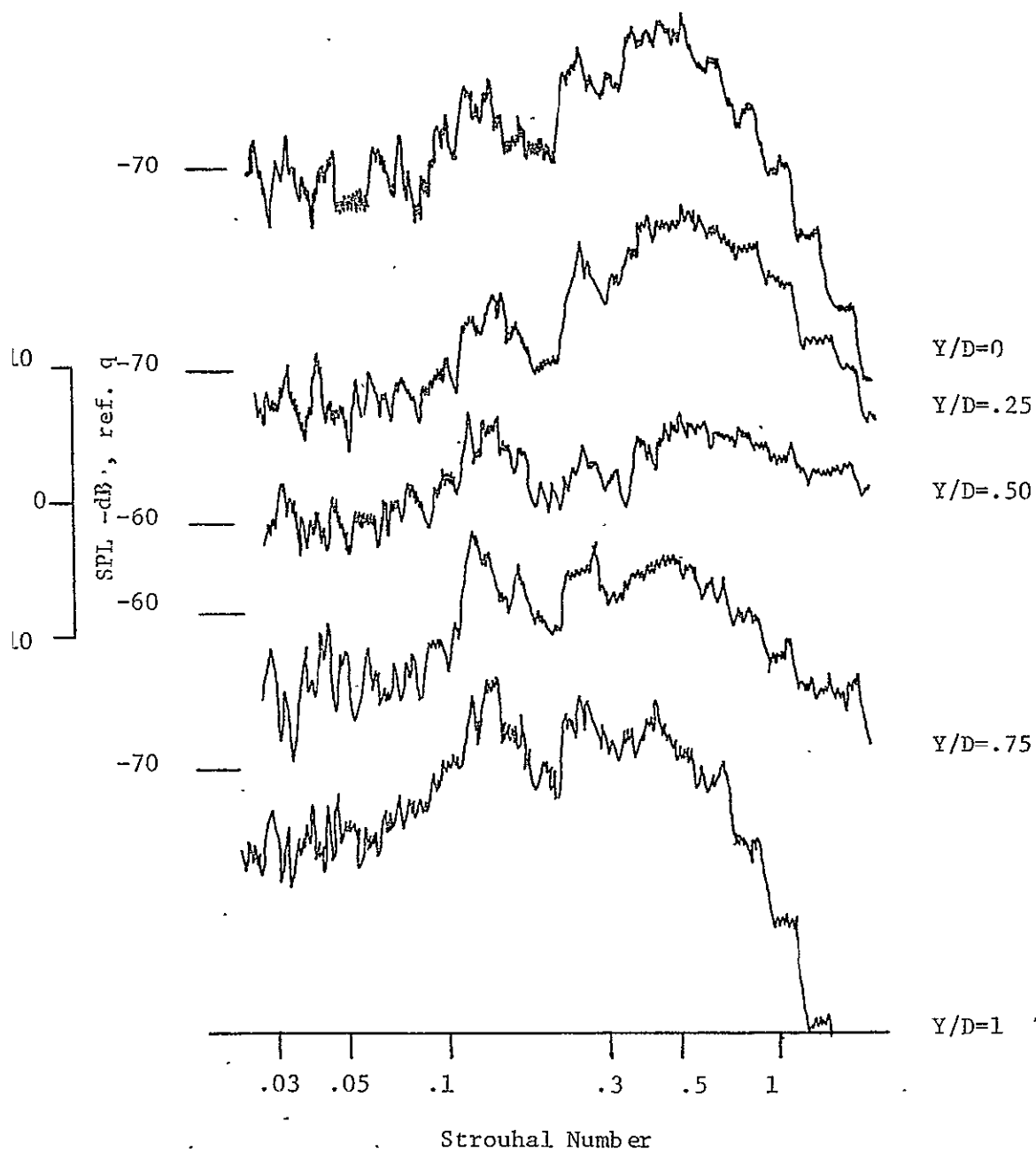


Figure 5.1.1 Free Jet 1/3 Octave Spectra: $X/D=2$

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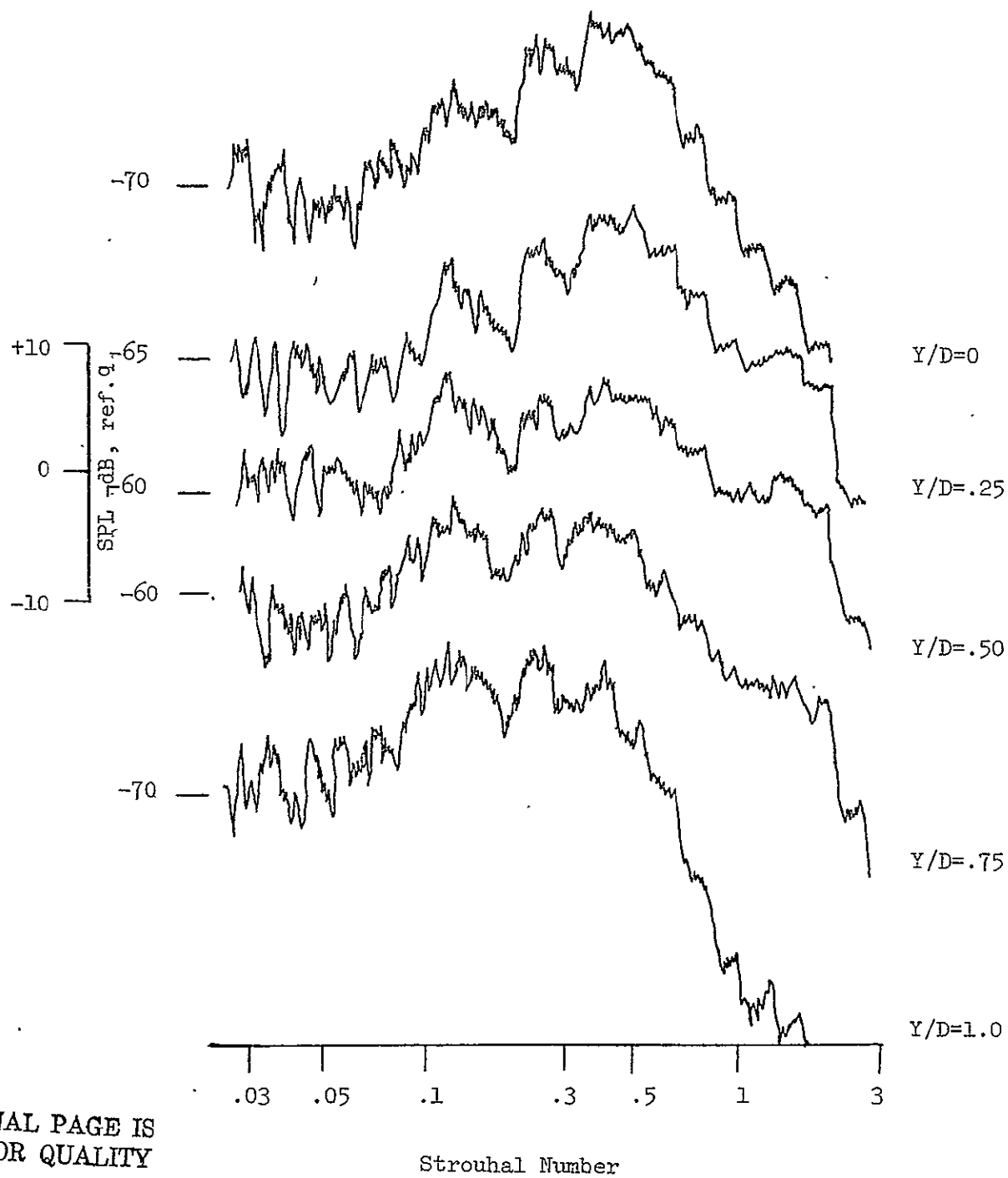


Figure 5.1.2 Free Jet 1/3 Octave Spectra: $X/D=3$

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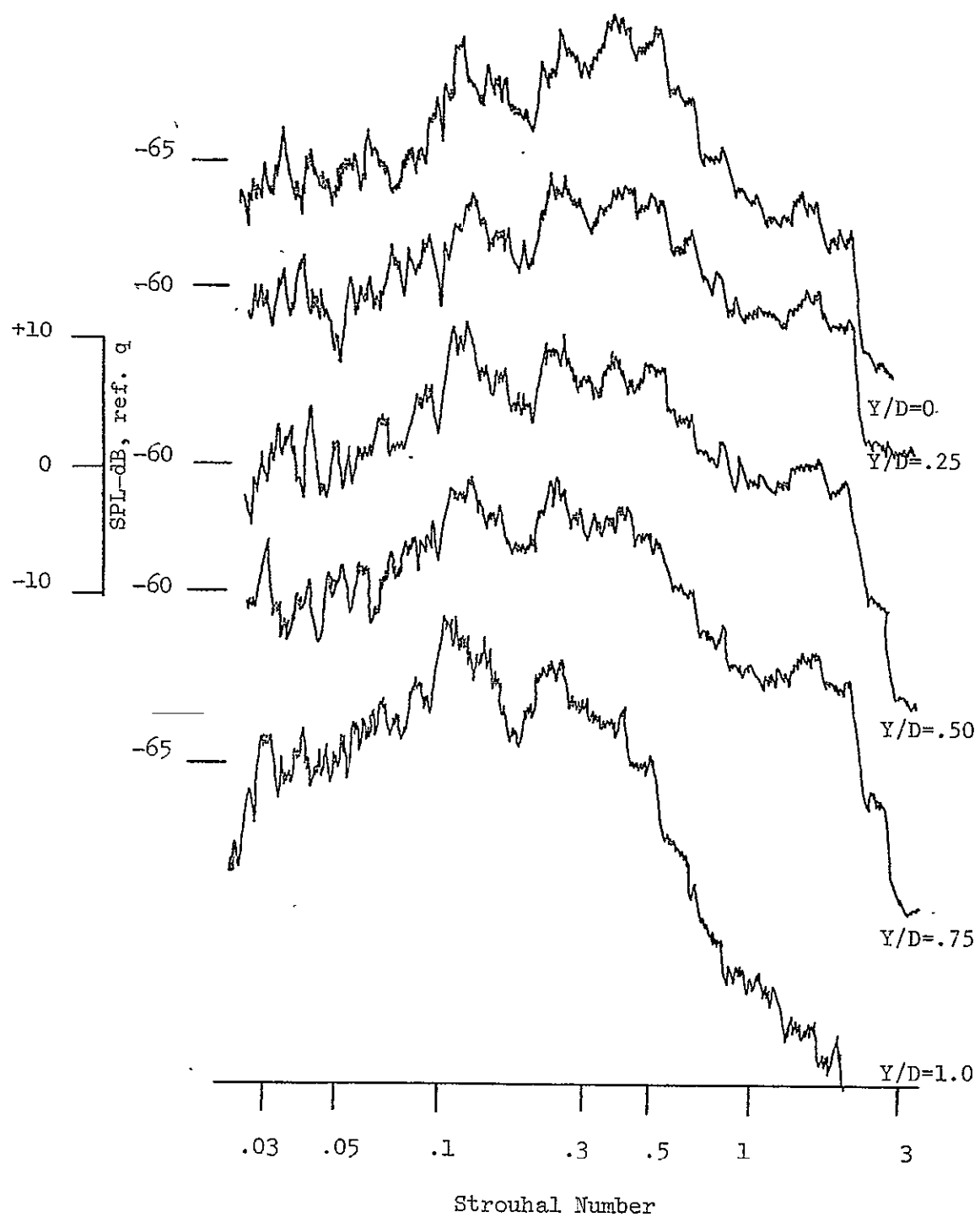


Figure 5.1.3 Free Jet 1/3 Octave Spectra: $X/D=4$

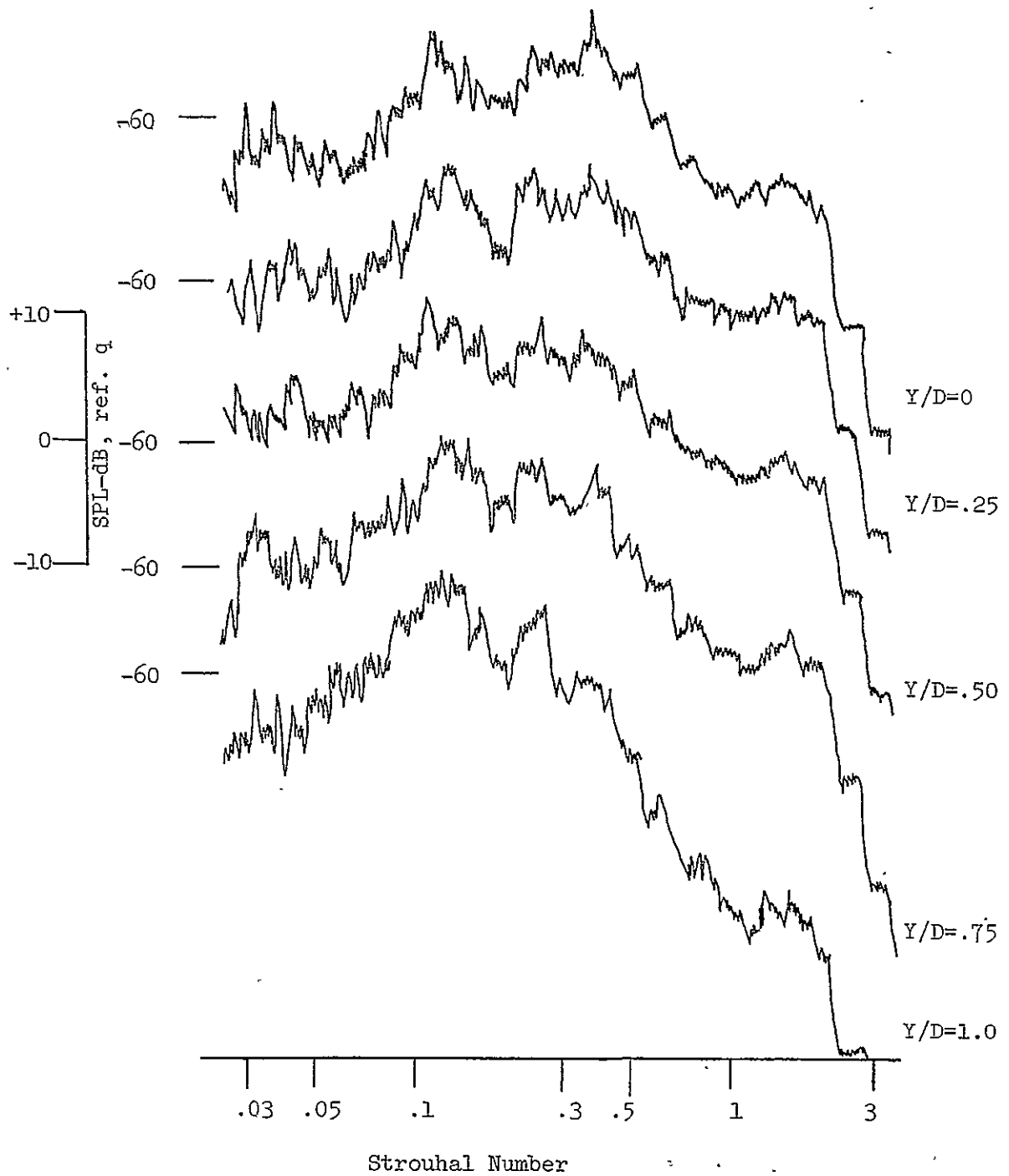


Figure 5.1.4 Free Jet 1/3 Octave Spectra: $X/D=5$

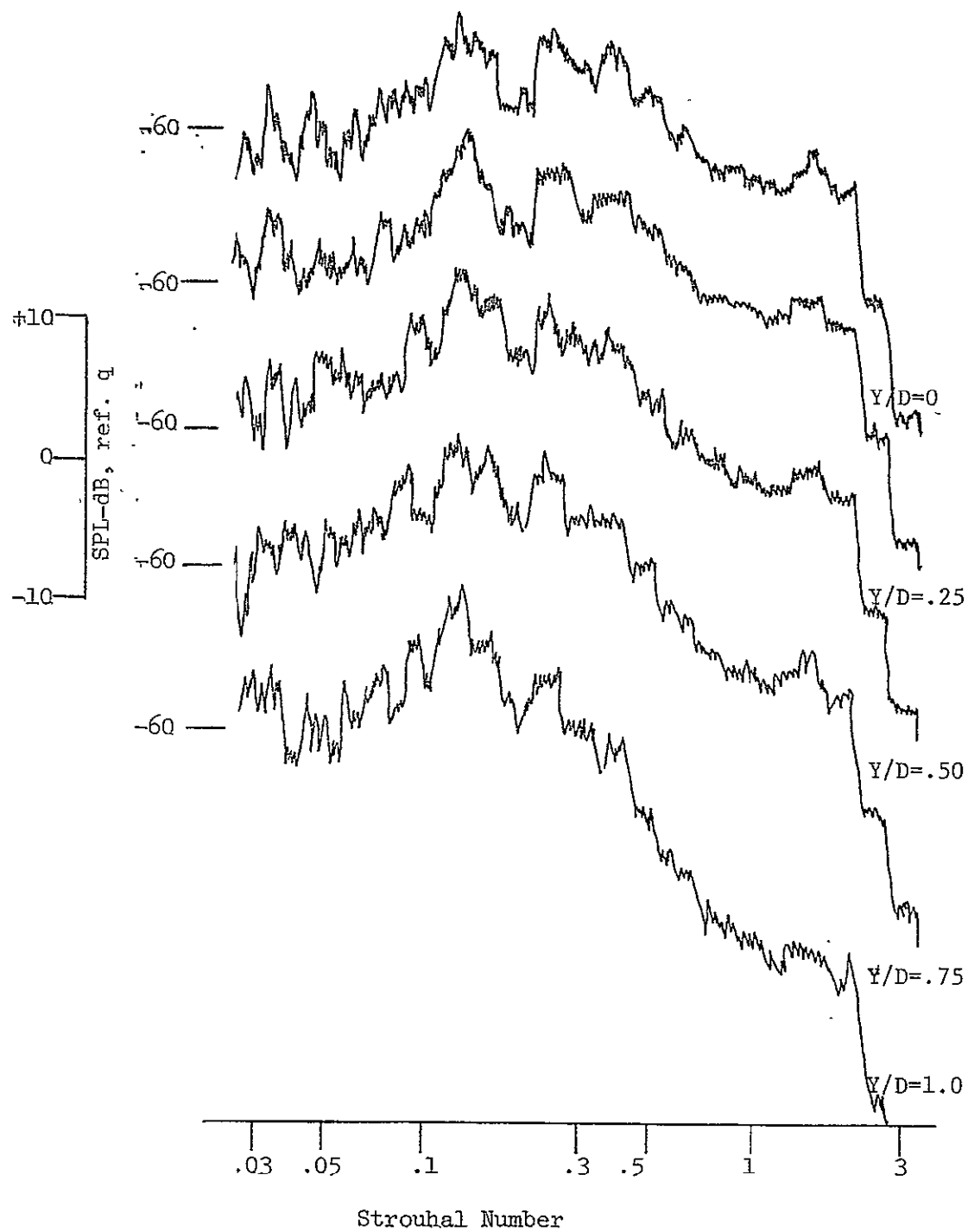


Figure 5.1.5 Free Jet 1/3 Octave Spectra: $X/D=6$

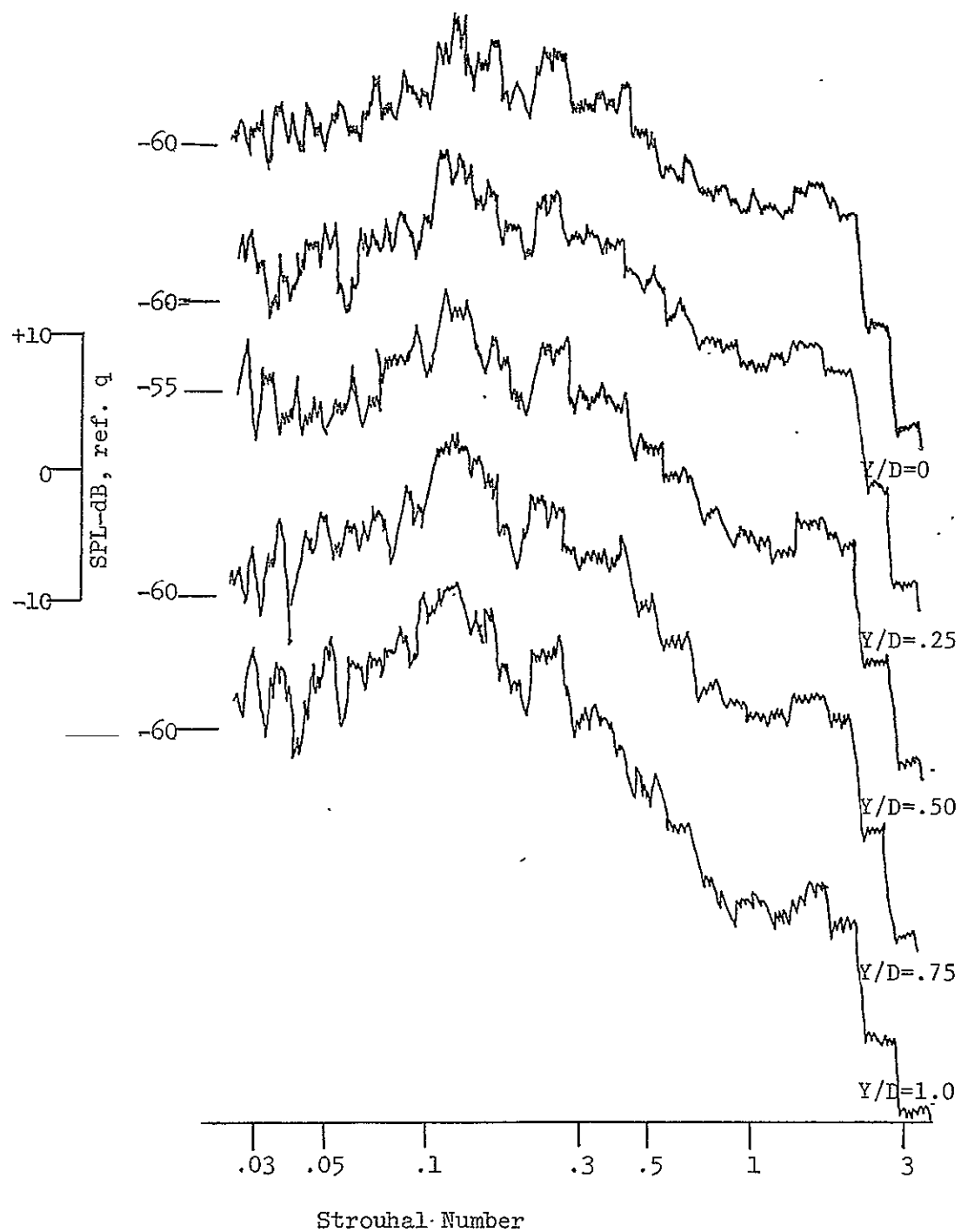


Figure 5.1.6 Free Jet 1/3 Octave Spectra: $X/D=8$

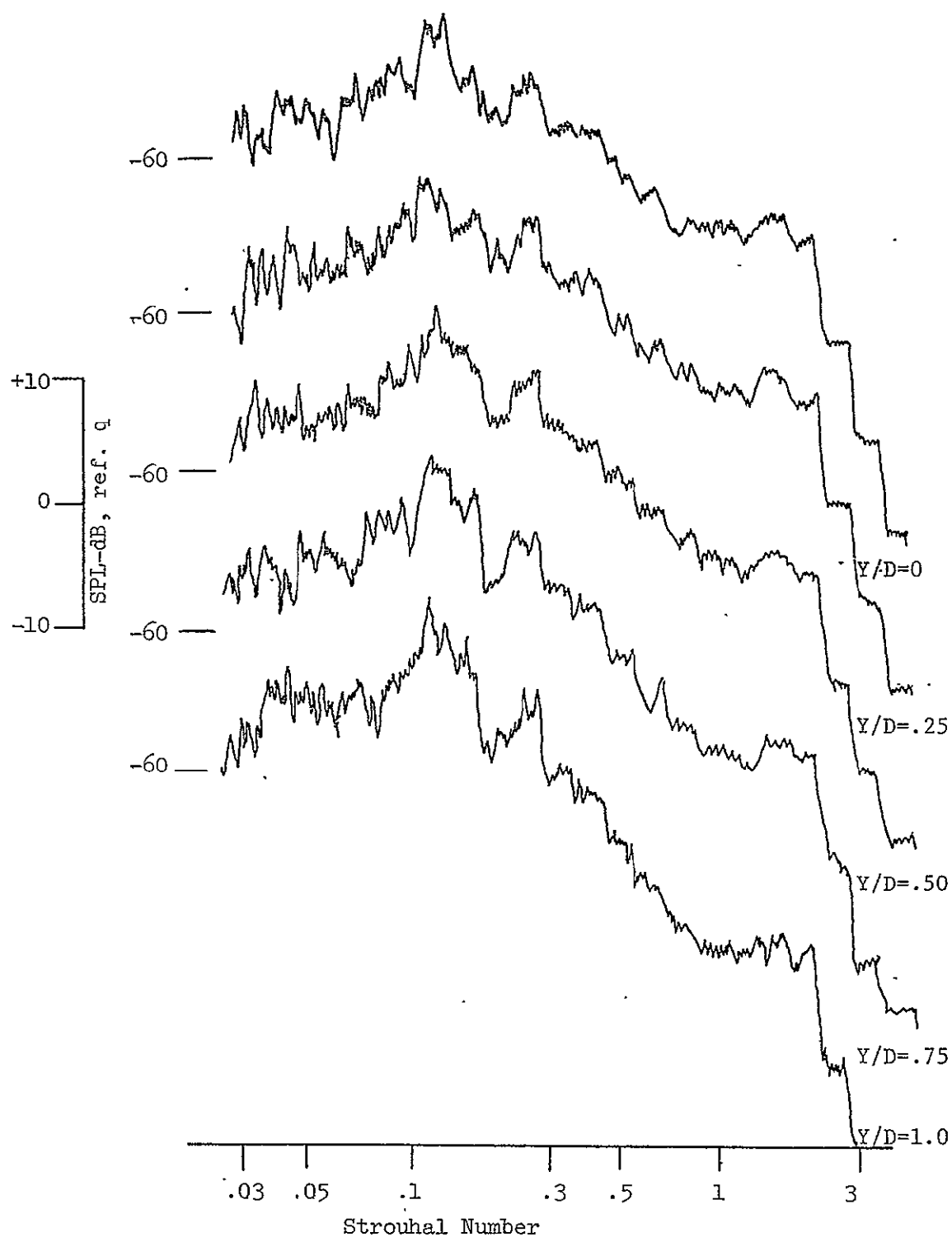


Figure 5.1.7 Free Jet 1/3 Octave Spectra: $X/D=10$

downstream, due to spreading of the sheared annulus. At locations of 6, 8 and 10 diameters downstream this peak is no longer present.

These spectra indicate that there is, within the initial zone, a dependence of the fluctuating pressure spectral content on the jet exit diameter. This dependence, noticed not only within the jet but also outside, is due to the spacing and rate of the low pressure wave passage associated with the vortex rings. The dependency is no longer present beyond the initial zone because the vortex rings are no longer dominant.

5.2 Free Jet - Correlation Coefficients

The maximum correlation coefficients versus radial probe separation at downstream locations between 2 and 10 jet diameters downstream are shown in Figures 5.2.1 and 5.2.2. Auto correlations and cross-correlations were taken with one probe on the jet center-line while the other probe was varied radially to give separations of up to 1.5 jet diameters. The definition of the maximum correlation coefficient is:

$$\text{Correlation Coefficient} = \frac{R_{12_{\max}}}{\sqrt{R_{11}(0) R_{22}(0)}}$$

The figures indicate high correlation coefficient values within the initial zone, the lowest point being within the sheared annulus region. Once outside the sheared annulus, the values of the correlation coefficients increase before they begin to decrease again. Downstream of the initial zone ($X/D=6,8,10$), values of the correlation

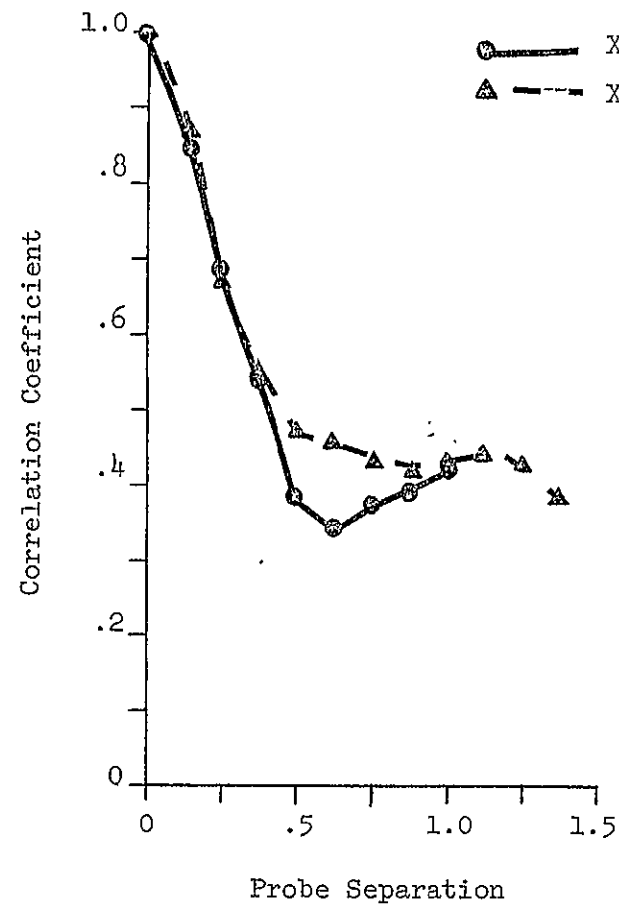
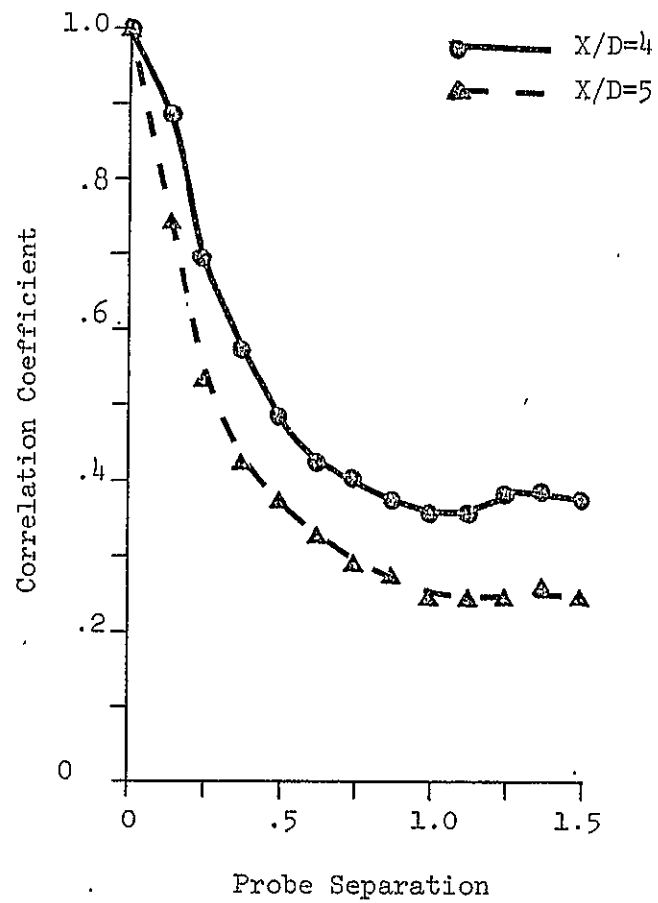


Figure 5.2.1 Free Jet Correlation Coefficients: $X/D=2-5$

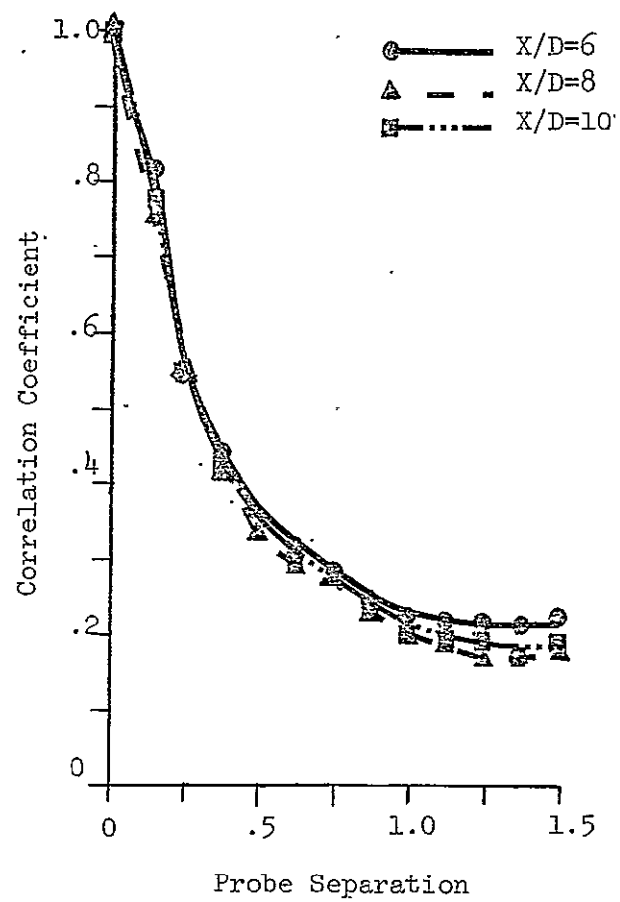


Figure 5.2.2 Free Jet Correlation Coefficients: $X/D=6, 8, 10$

coefficient decreases rapidly and approach zero with increased probe separation.

These figures of correlation coefficients tend to support the vortex model of a free jet. In the initial zone, the high value of correlation coefficients over large distances is due to the strong dependence on the vortex passage. Beyond the initial zone, correlation coefficients decrease rapidly with increased probe separation as is expected, because the vortex rings are no longer dominant.

5.3 Free Jet - Phase Lag, Transfer Function Amplitude and Coherence

The phase lag, transfer function amplitude and coherence relationships behind the free jet were investigated. Cross correlation information was obtained from two probes simultaneously, one always located on the jet centerline, while the other would be varied both radially and streamwise from this first probe. This information was then fed through the CROSSPECT computer program, giving phase lags, transfer function amplitudes and coherences versus Strouhal number.

Radial Relationships

The radial phase lag, transfer function amplitude and coherence relationships are shown in Figures 5.3.1 - 5.3.3. In the illustrated examples, one probe was located on the jet centerline, the other was varied radially outward from this first probe, at downstream locations of 2, 4, and 10 jet diameters.

The phase lags are found to be roughly equal to zero throughout the frequency range in all cases. This suggests that the fluctuating

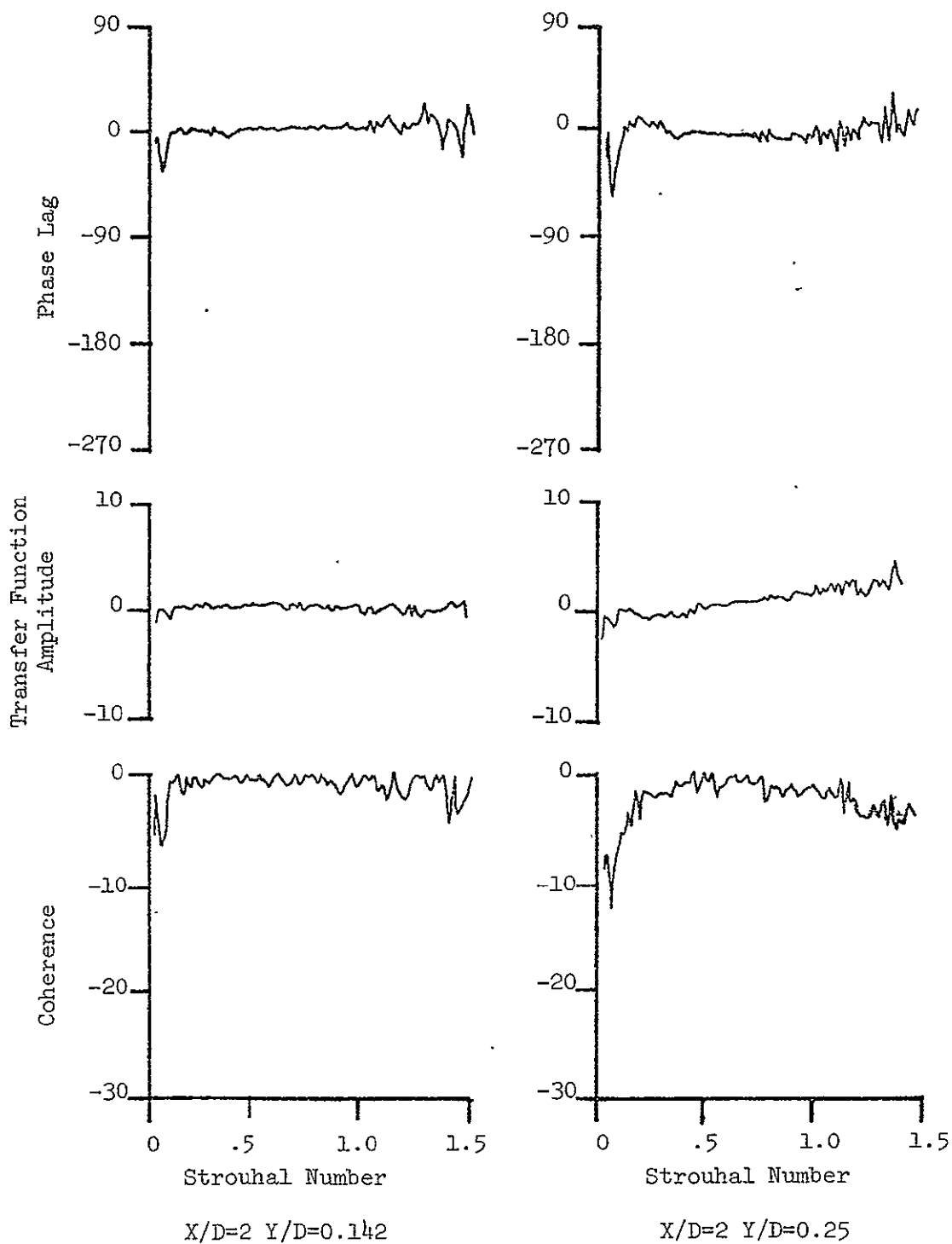


Figure 5.3.1 Free Jet Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $X/D=2$; $Y/D=0.142$ and 0.25

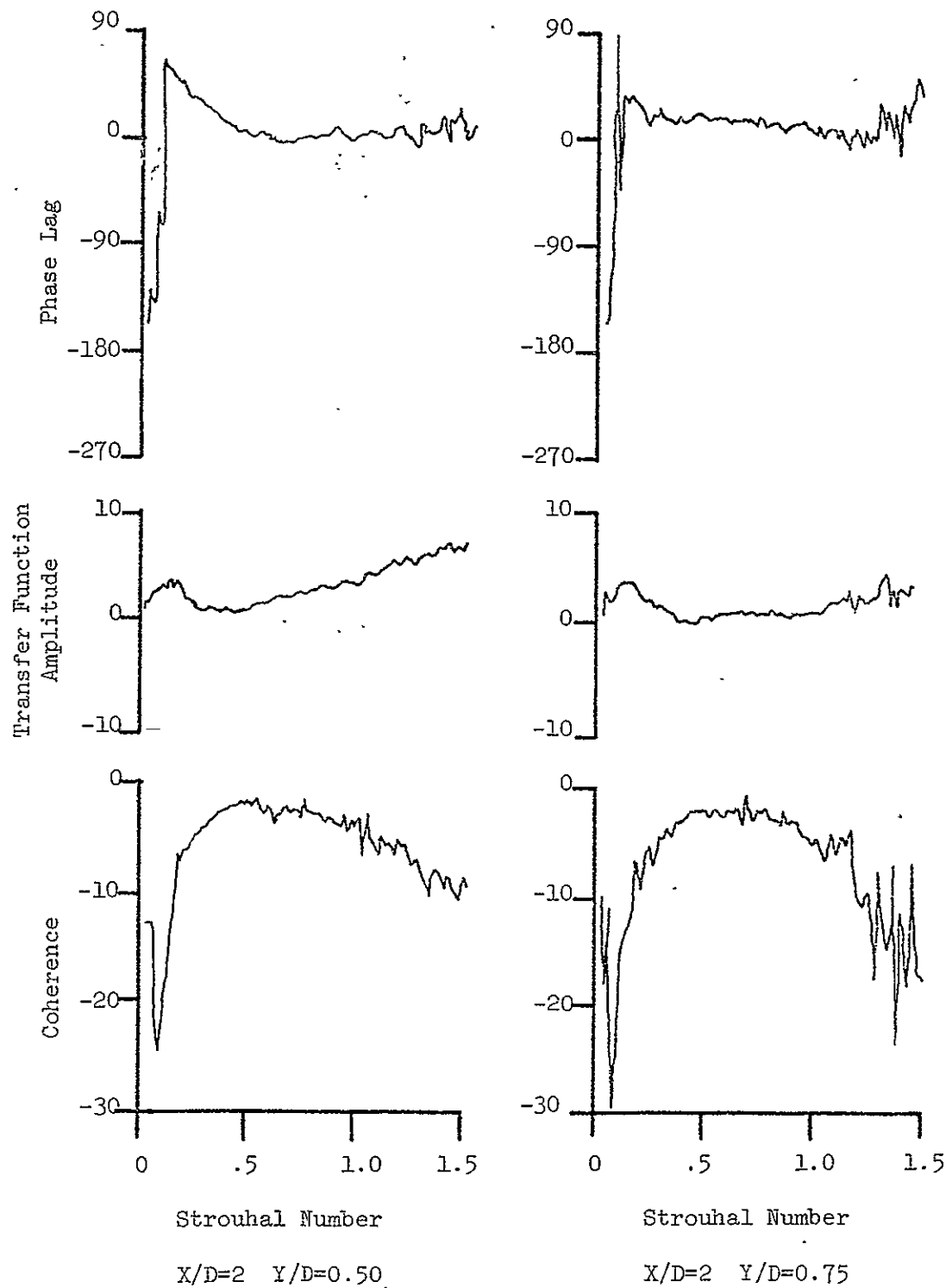


Figure 5.3.2 Free Jet Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $X/D=2$; $Y/D=0.50$ and 0.75

pressure disturbances are being sensed simultaneously by both probes and that the disturbances are not propagating in the radial direction. The transfer function amplitude curves show the relative frequency contents of the two probes.

The coherence at 2 diameters downstream is relatively high throughout the frequency range, with a maximum value of zero decibels at a Strouhal number of roughly 0.4. At 4 diameters, the coherence is generally lower, but still peaks at $St. No. = 0.4$. The coherence is low everywhere at a downstream location of 10 diameters. The vortex model of a jet predicts these high coherence peaks, at 2 and 4 diameters downstream, to be associated with the vortex ring passage, with no apparent passage at 10 diameters downstream, where the surrounding turbulence dominates.

Axial Relationships

The axial phase lag, transfer function amplitude and coherence relationships as a function of Strouhal number are shown in Figures 5.3.4 and 5.3.5. The probes are located along the jet centerline, radially next to each other, but with a 1.0 cm streamwise separation. The illustrated examples are at 1, 2, 4, and 10 jet diameters downstream.

The transfer function amplitude curves are roughly equal to zero throughout the frequency range and also the coherences are high. These high values are expected, because of the proximity of the probes, degenerating with increased downstream location.

The phase lags between the two probes show a small variation with frequency. The average slopes of these phase lag curves give the mean convection velocity of the propagated pressure disturbances by the

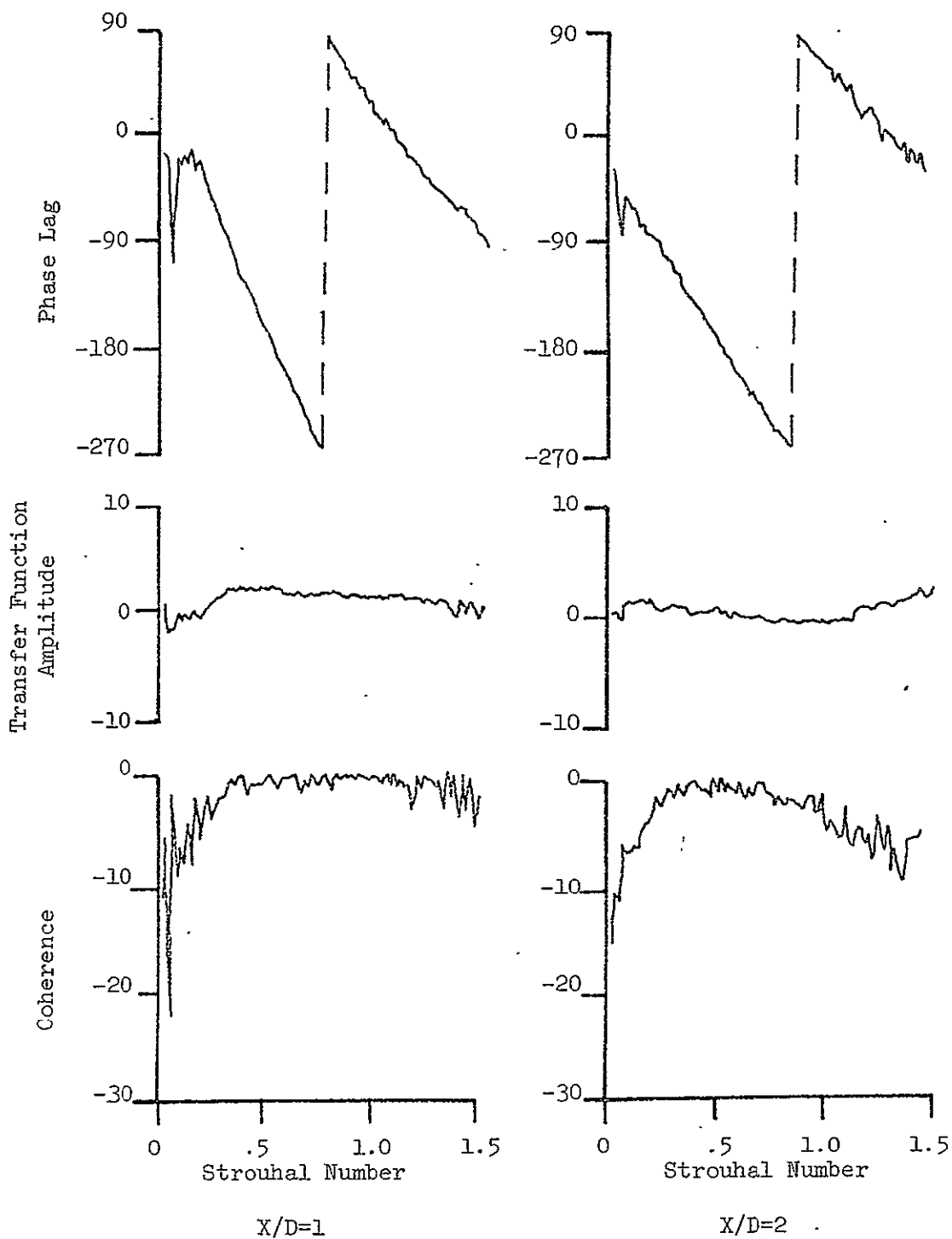


Figure 5.3.4 Free Jet Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
Probe Separation=1.0 cm; $X/D=1$ and 2

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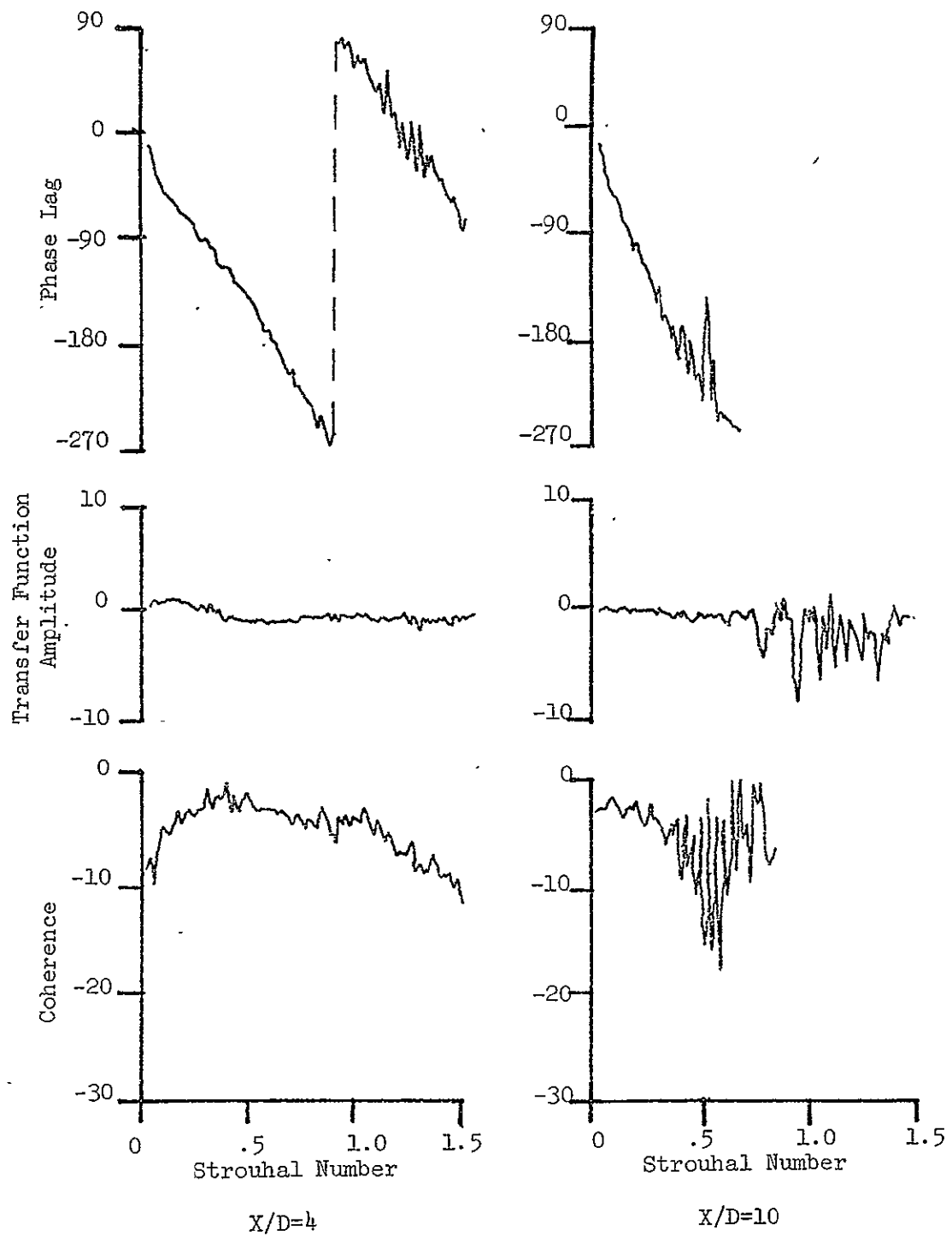


Figure 5.3.5 Free Jet Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 .Probe Separation-1.0 cm; $X/D=4$ and 10

following relationship [relative to jet exit velocity]:

$$\frac{U_c}{U_j} = \frac{360 \Delta x}{D_j} \frac{\Delta \text{St. No.}}{\Delta \theta} \quad (\Delta x = \text{probe separation})$$

The streamwise convection velocities, calculated from these plots, are shown in Table 2. The values of convection are found to be between 0.6 to 0.8 times the jet exit velocity. This demonstrates that the pressure disturbances are propagating downstream at relative convection speeds.

Table 2

Free Jet - Convection Velocities

<u>Downstream Location</u>	<u>U_c/U_j</u>
1	.6
2	.8
4	.8
10	.6

5.4 Jet Impingement - Fluctuating Pressure Levels

The overall surface fluctuating pressure levels on the flat plate at various downstream locations and angular orientations were investigated. The center of the plate was positioned at 2, 4, and 6 jet diameters downstream and the plate impingement angle was set at 0° (normal impingement), 30°, 60°, and 90° (grazing impingement). Figure 5.0.1 shows how the plate was situated in the jet flow except for the special case of grazing impingement, where the plate was located along the lip of the jet. The rms surface pressure levels for these different

orientations are illustrated in Figures 5.4.1 - 5.4.4. In these figures, the levels are given in decibel form referenced to q .

The variation of downstream locations at the various impingement angles indicates that initially the potential core region is present at 2 and 4 diameters downstream, with peak fluctuations occurring within the sheared annulus region. The largest fluctuating pressure levels are seen to occur upstream of the plate center, along the projected jet centerline.

The study of the effects of plate inclination angle indicated that the overall fluctuating surface pressure levels tend to decrease with increasing plate inclination angle, the highest levels occurring at normal impingement. For the special case of grazing impingement, the lowest overall levels were measured, with the levels of the upstream plate locations only slightly higher than at other plate locations. Also, the levels in the radial direction begin to drop off quickly at larger distances from the plate center, indicating that the edge of the jet has been reached.

These figures indicate that the area of highest fluctuating pressure levels is found at the upstream locations of the jet. This is a complex flow region, for both induced flow down the plate and direct impingement flow up the plate are encountered. The levels decrease with increasing impingement angle, grazing impingement having the lowest levels.

5.5 Jet Impingement - 1/3 Octave Spectra

Figures 5.5.1 - 5.5.9 show the 1/3 octave fluctuating surface pressure surface at various locations on the flat plate. The levels are

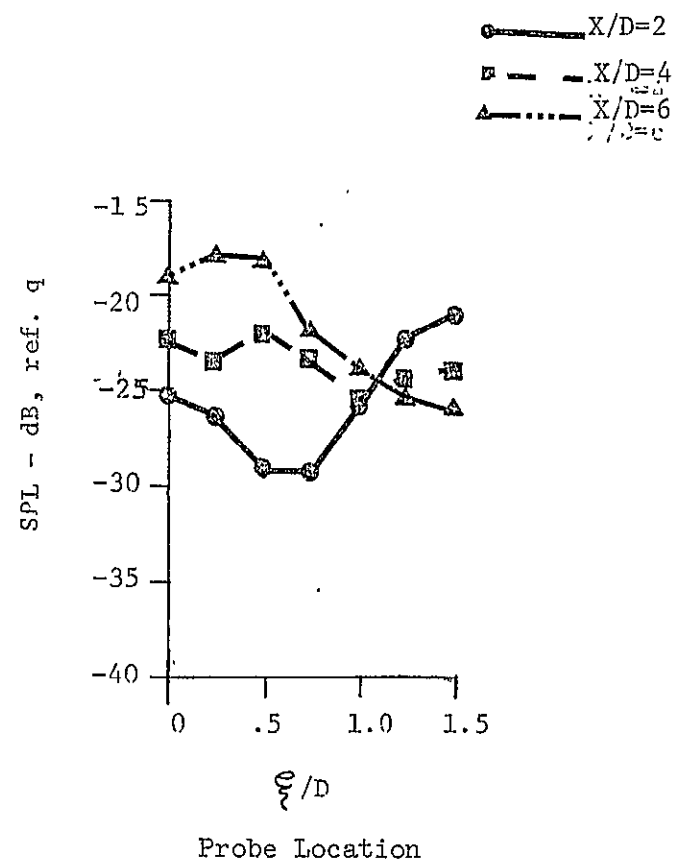


Figure 5.4.1 Jet Impingement Fluctuating Pressure Levels: $\beta = 0^\circ$

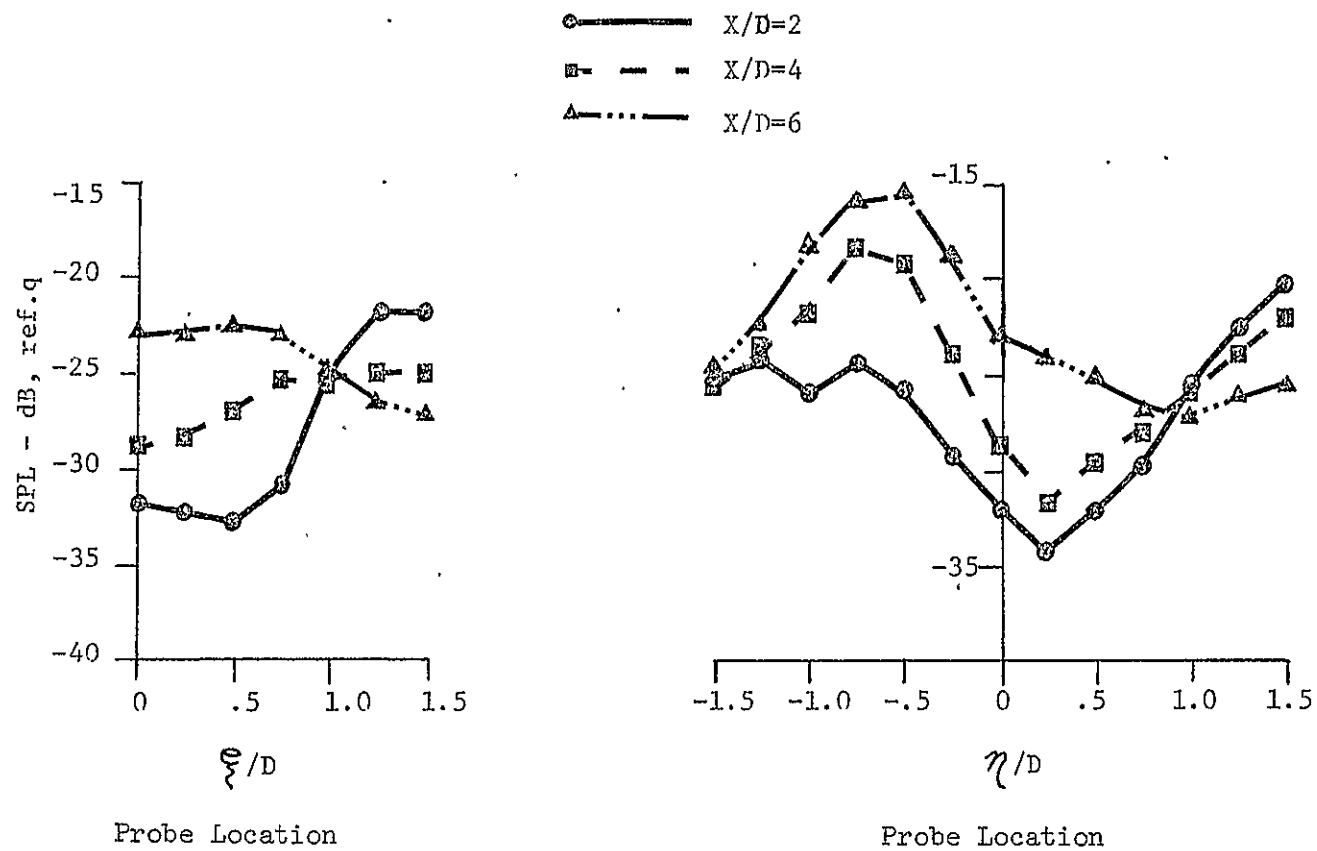


Figure 5.4.2 Jet Impingement Fluctuating Pressure Levels: $\beta=30^\circ$

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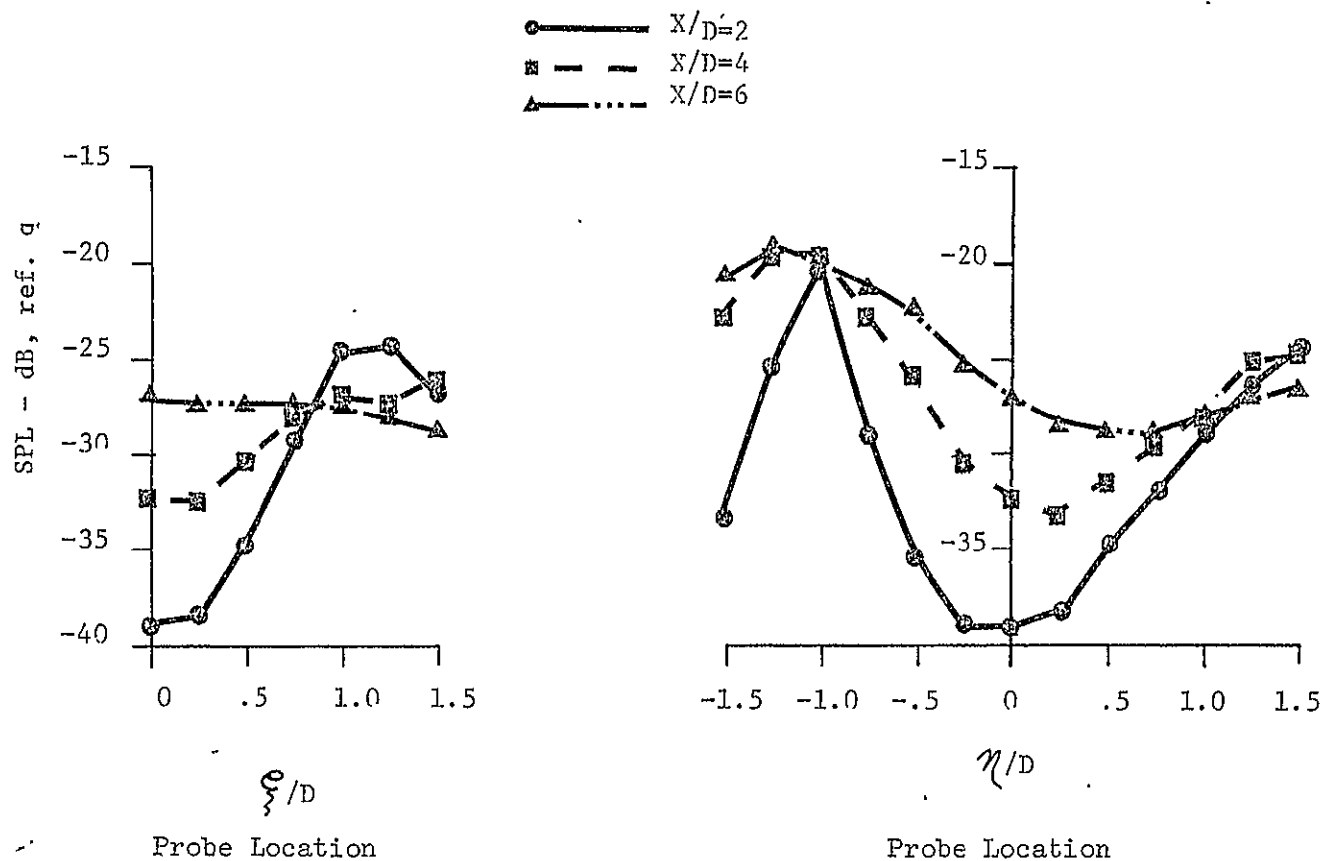


Figure 5.4.3 Jet Impingement Fluctuating Pressure Levels: $\beta=60^\circ$

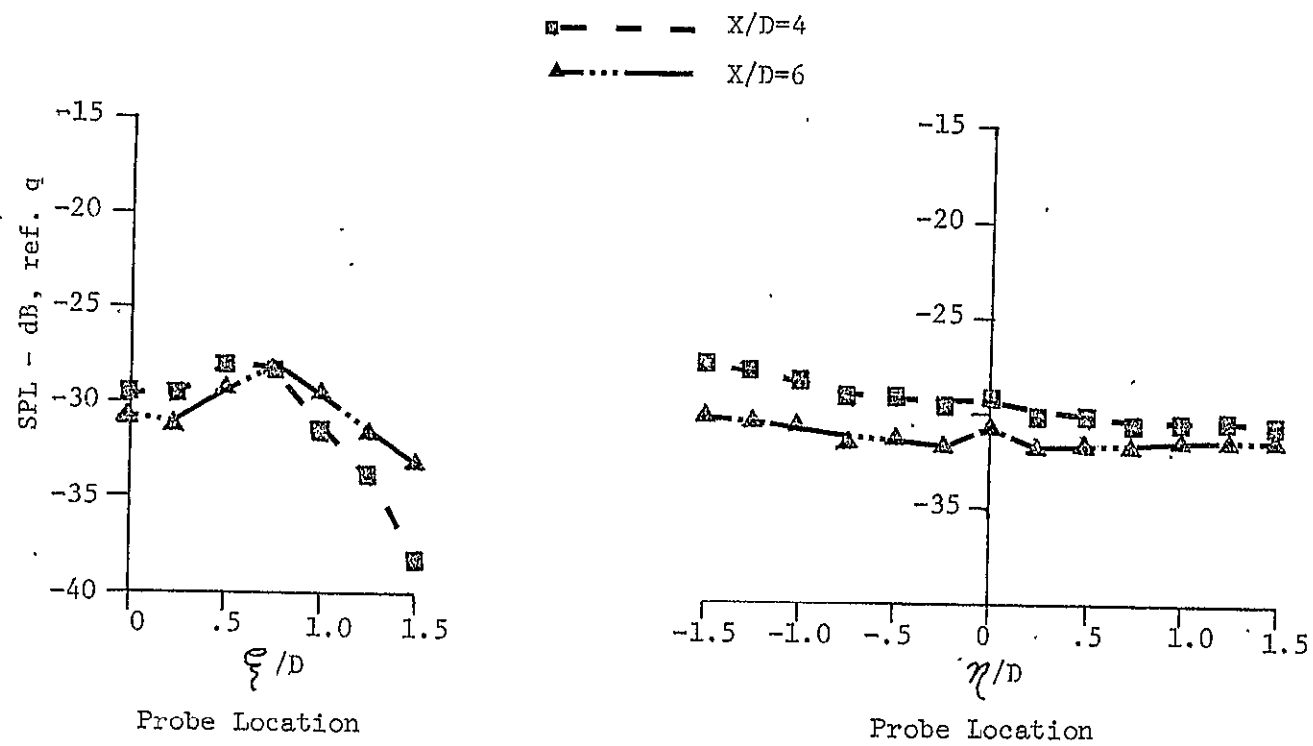


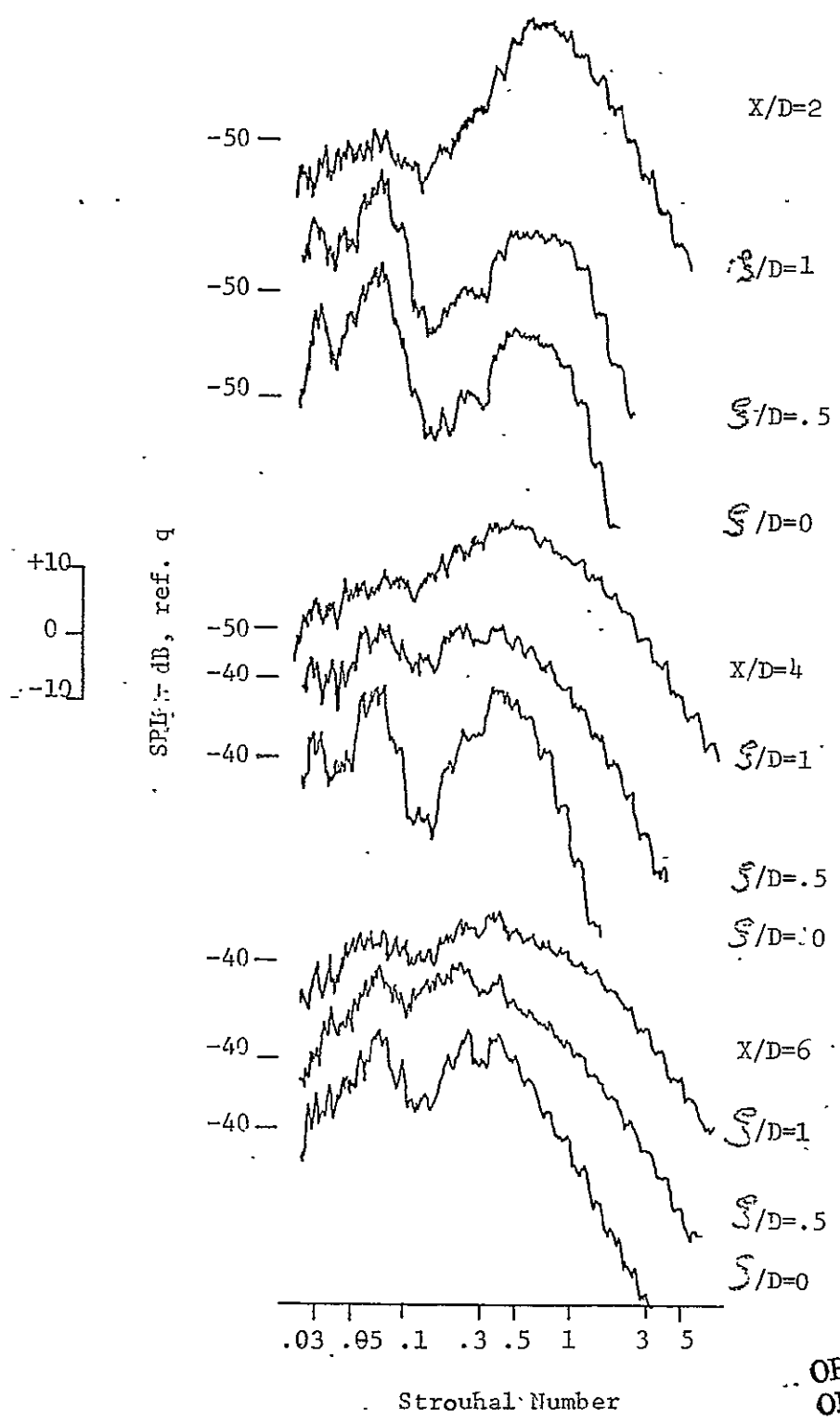
Figure 5.4.4 Jet Impingement Fluctuating Pressure Levels: $\beta=90^\circ$

given in decibel form referenced to q and the frequency scale has been converted to Strouhal number form. In each figure (except for symmetric case of normal impingement) eight spectra are presented, corresponding to different pressure port locations in the radial and streamwise directions. The plate was positioned at 2, 4, and 6 diameters downstream with impingement angles of 0° , 30° , 60° , and 90° .

These spectra display the same basic phenomena as the free jet except for a few notable exceptions. The most important influence of the plate inserted into the free jet, is the overall increase in the fluctuating pressure levels, the Strouhal number peak dependence being even more predominant, again at 0.3 to 0.4.

A second peak, not evident in the free jet study, appears at port locations within the projected diameter of the jet. The cause of this phenomena is not as yet clearly understood. It does not seem to be acoustical in nature, for it is not sensed at all port locations, as would be expected because of the large wave length associated with this low frequency. It also does not seem to be vibrational in character for again the fluctuations at these particular frequencies are confined to a specific area.

This phenomenon is dominant when the plate is closest to the jet exit and this dominance decreases with increased impingement angle. A possible cause for this secondary peak is a disturbance of the fluctuating dynamic pressure component of the field caused by the rotational speed of the jet fan blower system. This fan rotation could cause a tripping of the flow disturbances equivalent to the disturbances tripped



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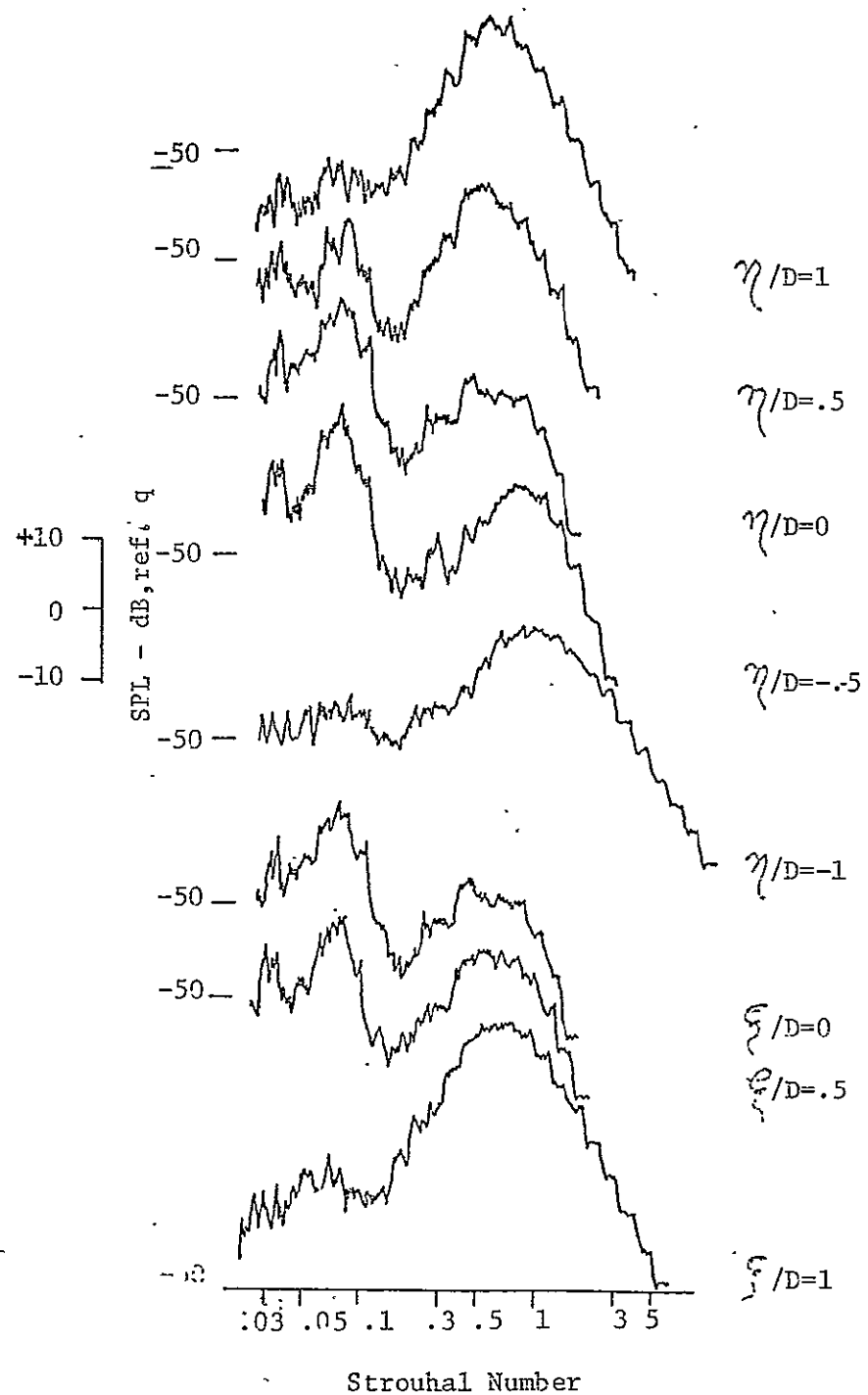


Figure 5.5.2 Jet Impingement 1/3 Octave Spectra: $X/D=2$, $\beta=30^\circ$

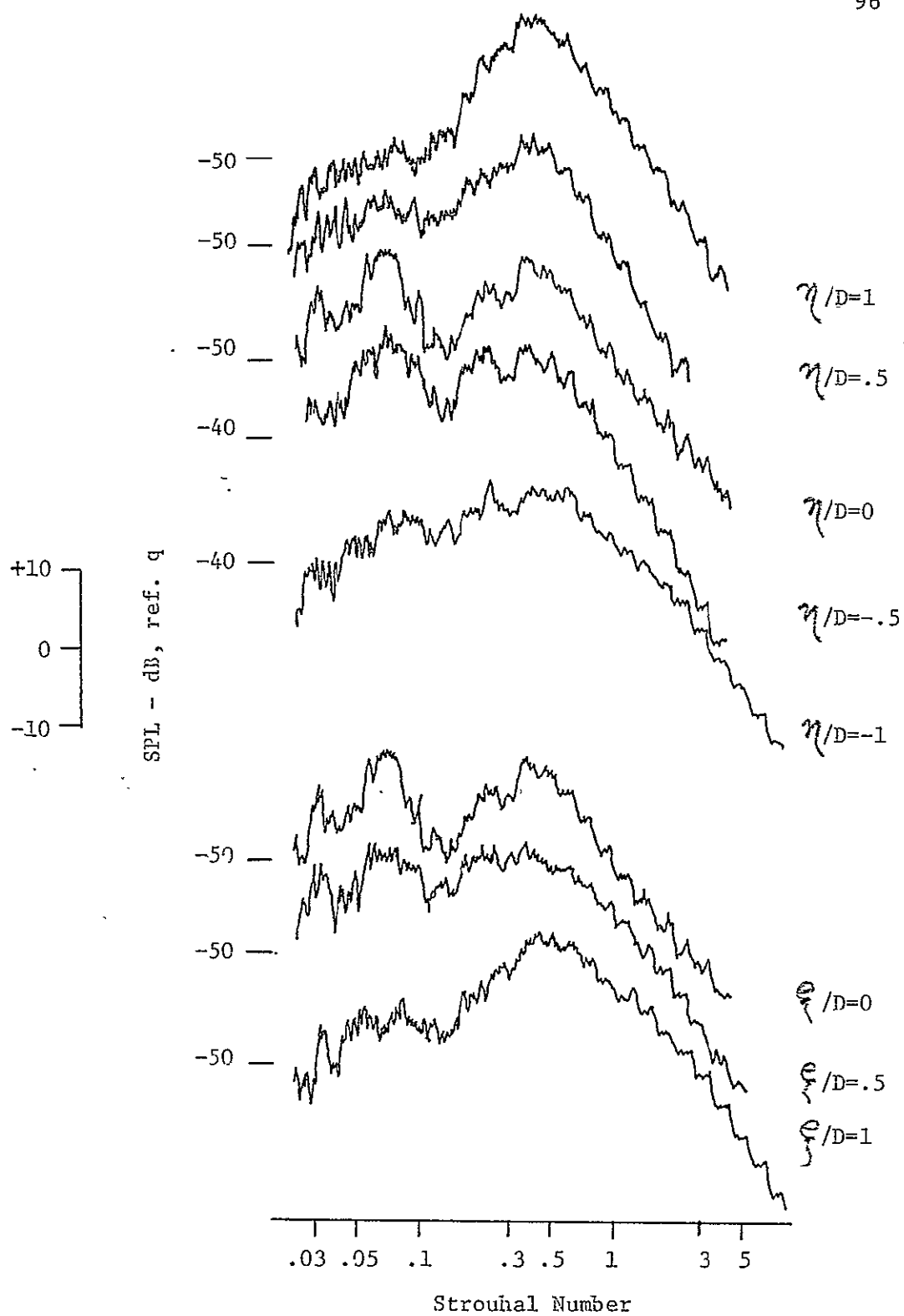


Figure 5.5.3 Jet Impingement 1/3 Octave Spectra $X/D=4$, $\beta=30^\circ$

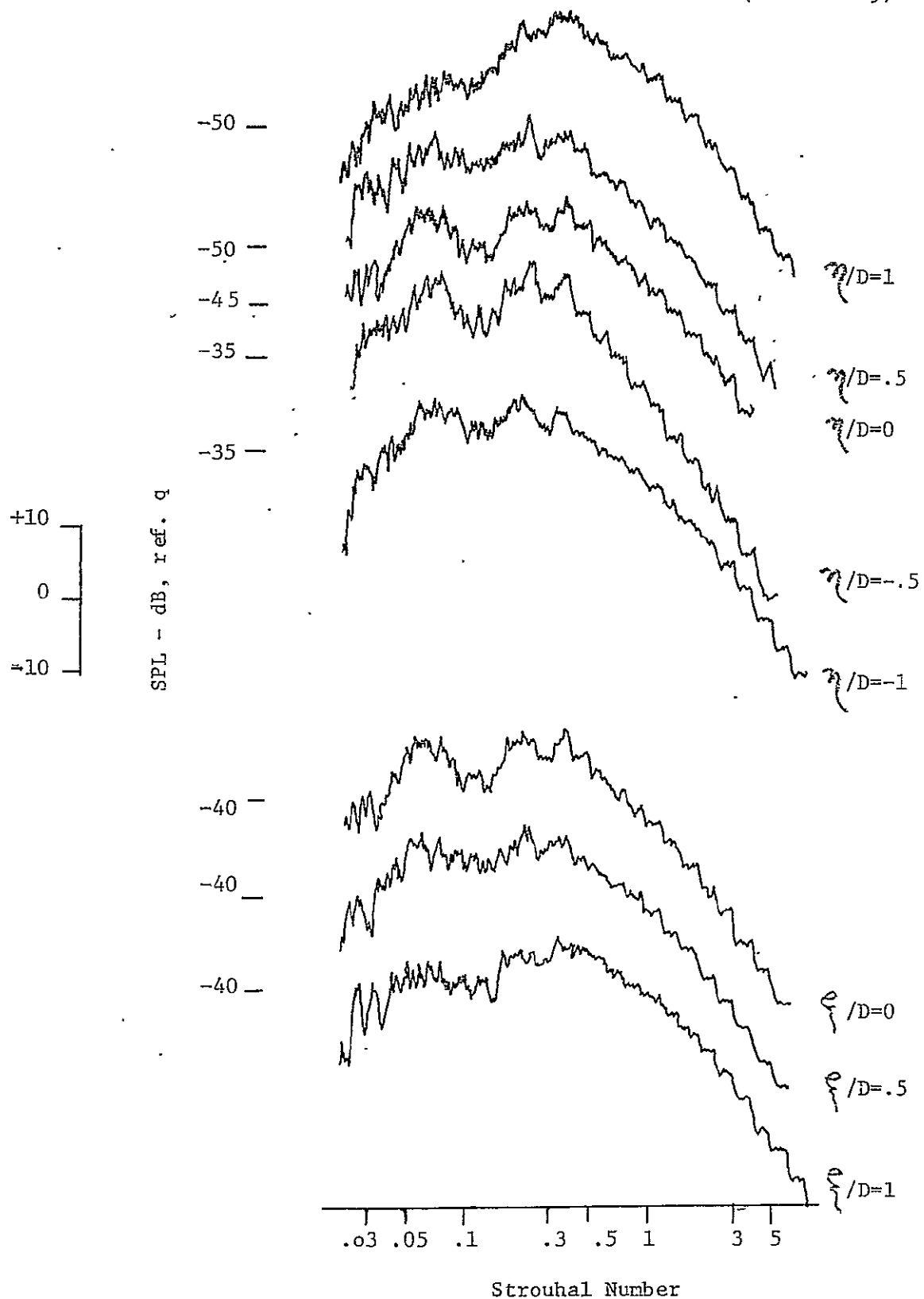


Figure 5.5.4 Jet Impingement 1/3 Octave Spectra: $X/D=6$, $\beta=30^\circ$

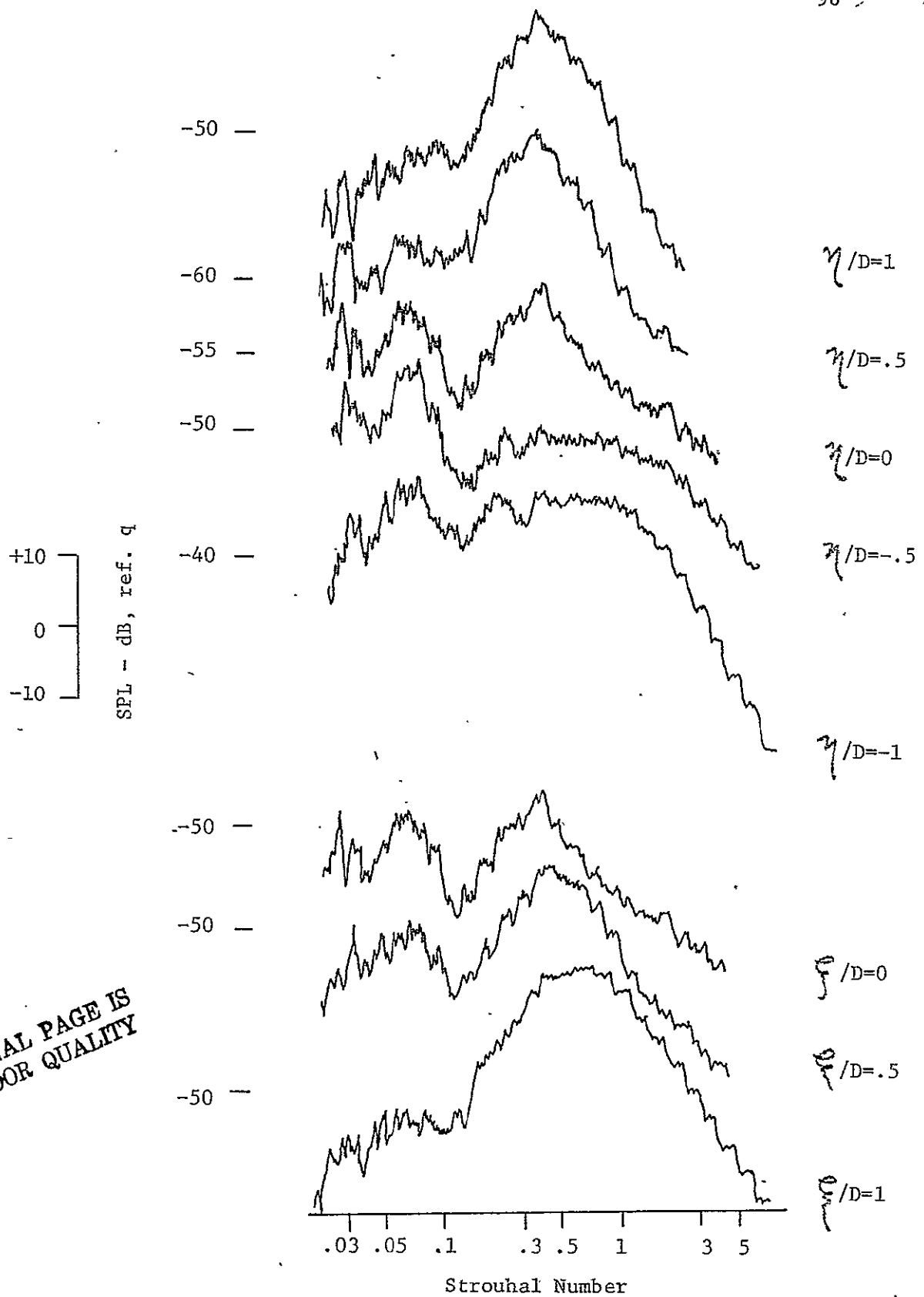


Figure 5.5.5 Jet Impingement 1/3 Octave Spectra: $X/D=2$, $\beta=60^\circ$

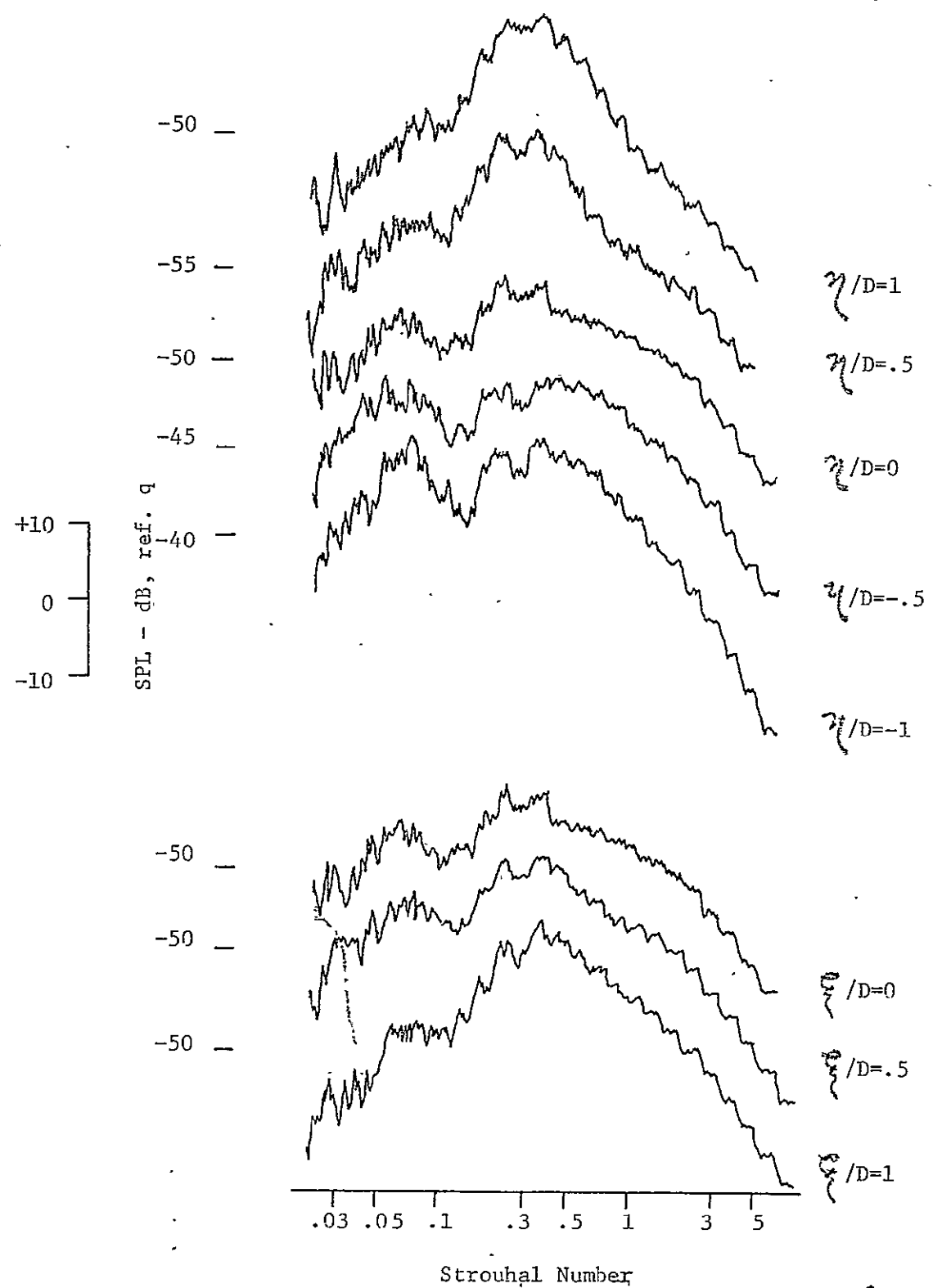


Figure 5.5.6 Jet Impingement 1/3 Octave Spectra: $X/D=4, \beta=60^\circ$

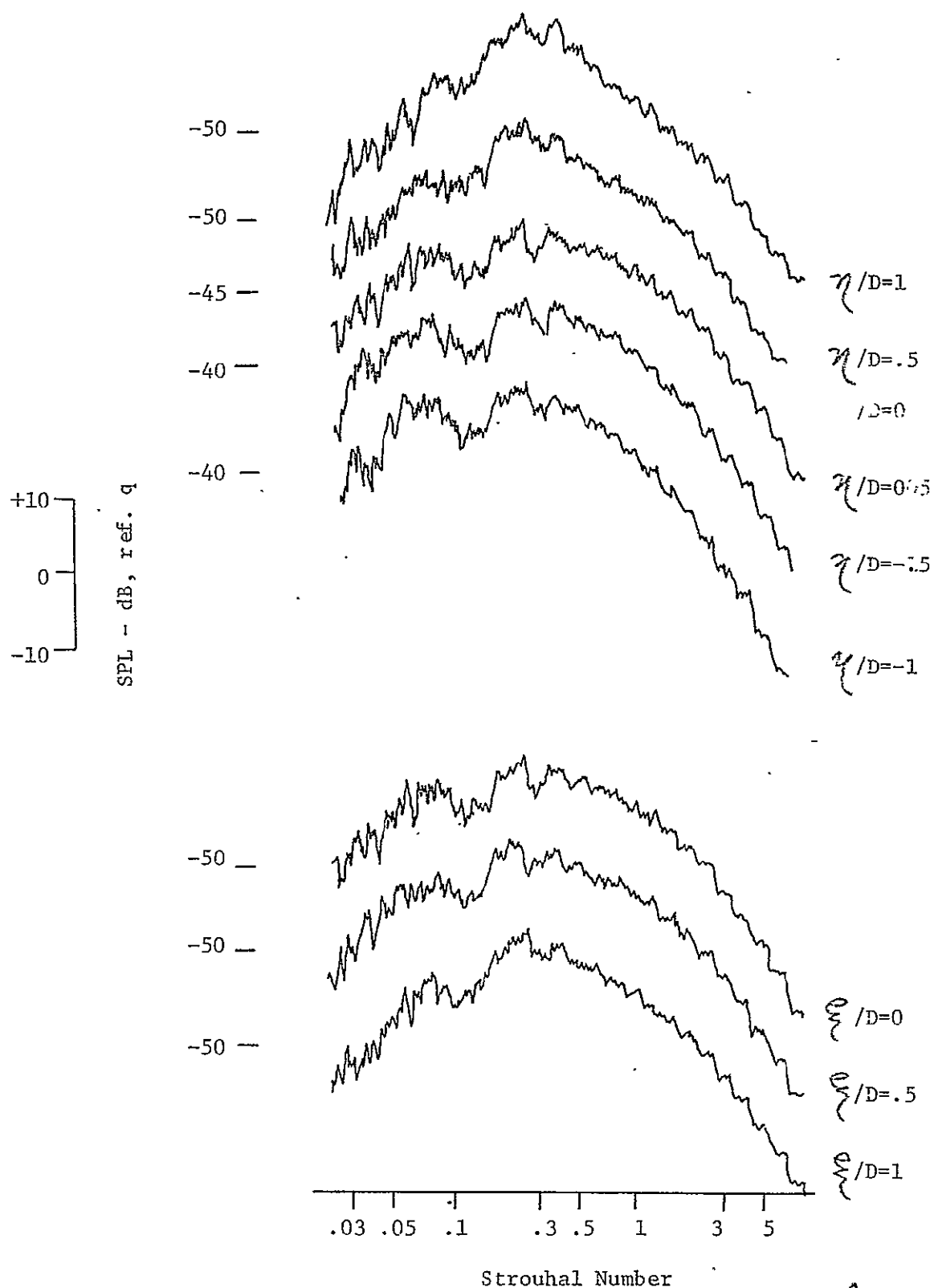


Figure 5.5.7 Jet Impingement 1/3 Octave Spectra: $X/D=6$, $\beta=60^\circ$

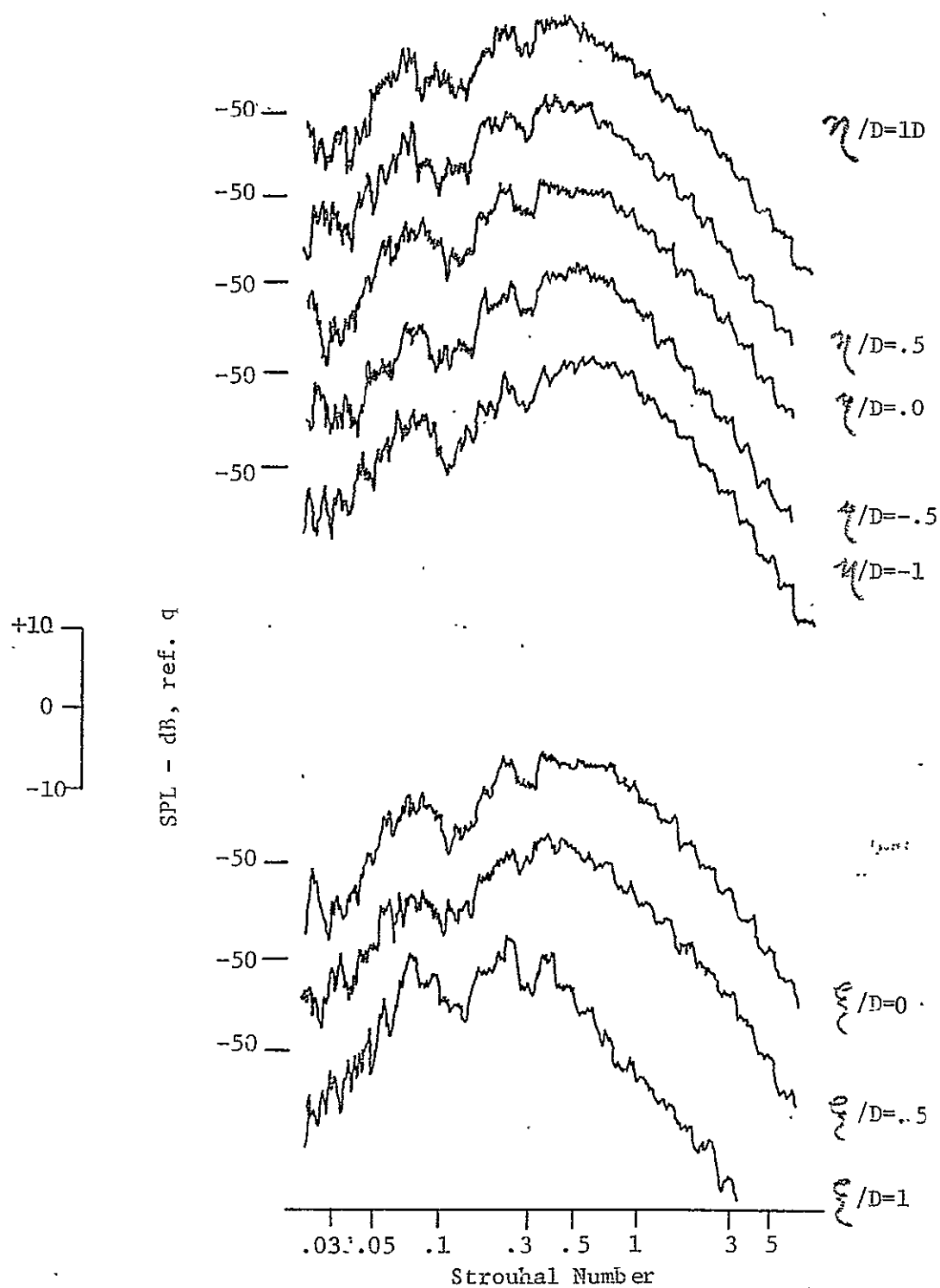


Figure 5.5.8 Jet Impingement 1/3 Octave Spectra: $X/D=4$, $\beta=90^\circ$

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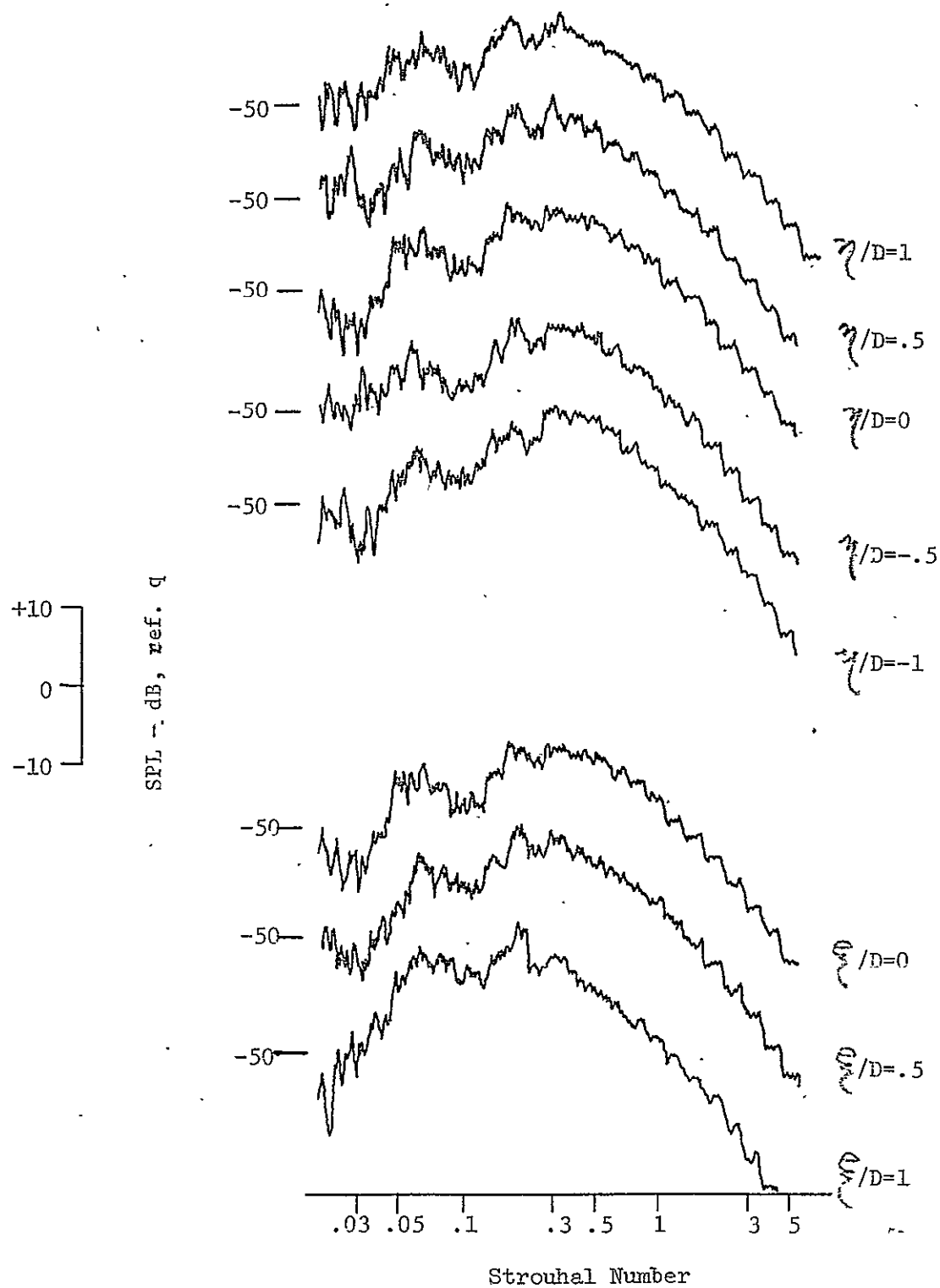


Figure 5.5.9 Jet Impingement 1/3 Octave Spectra: $X/D=6$, $\beta=90^\circ$

acoustically in the studies of Crow and Champagne.⁽⁶⁾ These disturbances are confined to the potential core and increasing the impingement angle increases the vortex type structure propagates up the plate wiping out these disturbances. However, when the fluctuating pitot probes were used behind the jet this secondary peak was not evident. This evidence also seems to indicate that the phenomenon is associated with an interaction between the plate and the exit of the jet. It has been reported that an acoustical feed back mechanism has been experienced in other studies,⁽²¹⁾ however, they found that at low speed, equal to those in this investigation, the mechanism, if present at all, would be extremely weak and unstable. Thus, the true nature of this secondary peak is as yet unclear and needs some further investigation.

5.6 Jet Impingement - Correlation Coefficients

Figures 5.6.1 - 5.6.5 show maximum correlation coefficients of surface probes in jet impingement versus probe separation at various downstream locations and impingement angles. The coefficients were calculated by correlating the signal from two of the plate's pressure ports. The plate center port was always used and the other was varied, giving different lateral or streamwise separation along the plate, up to 1.5 jet diameters.

These figures indicate high coefficient values, which increase as impingement varies from normal to grazing. However, the correlation coefficients are low for the upstream separations. This is due to the complexity of the flow field caused by the interaction of the induced flow and the direct impingement flow. These figures seem to indicate that the disturbances spread outwards after impinging on the plate

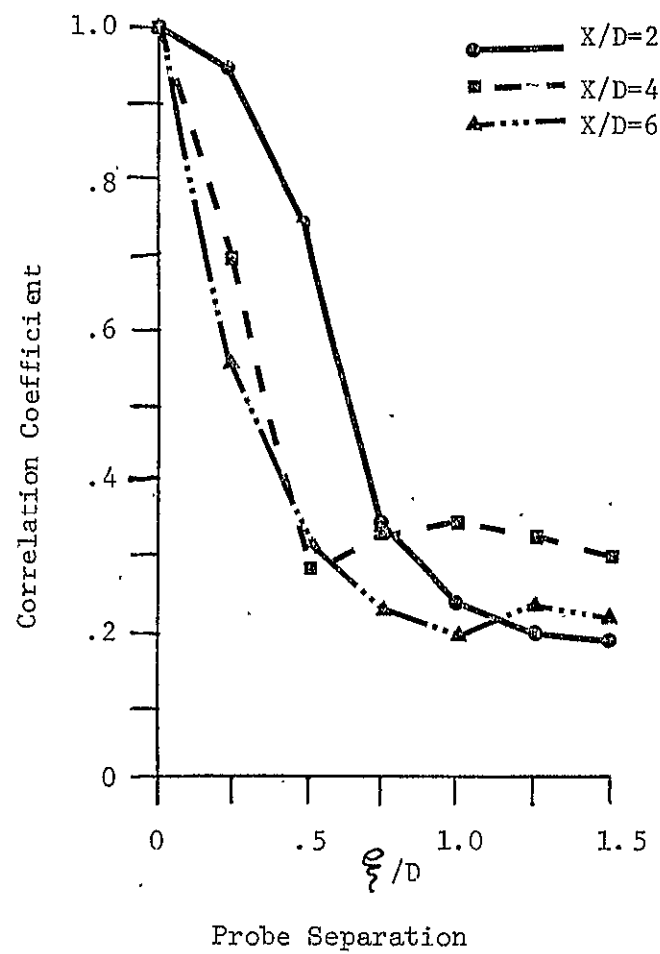
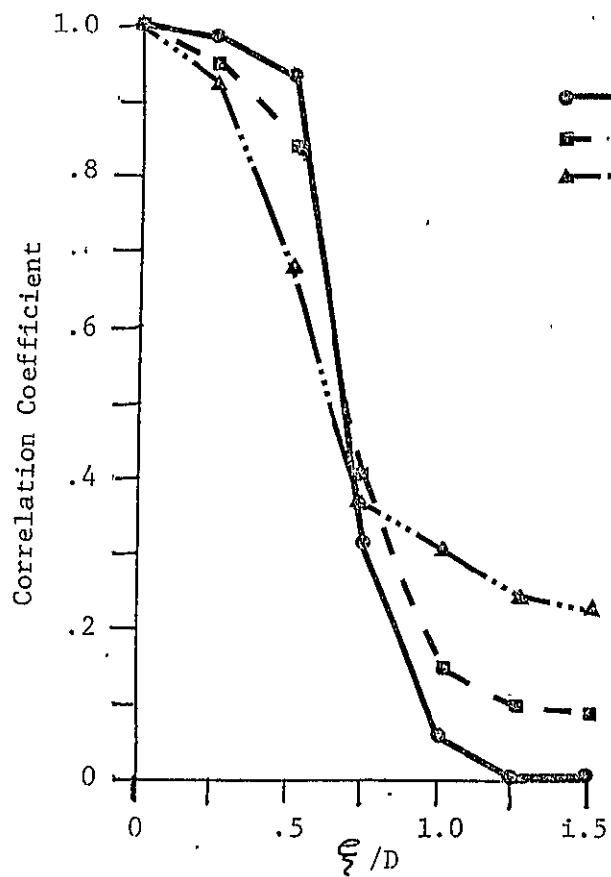
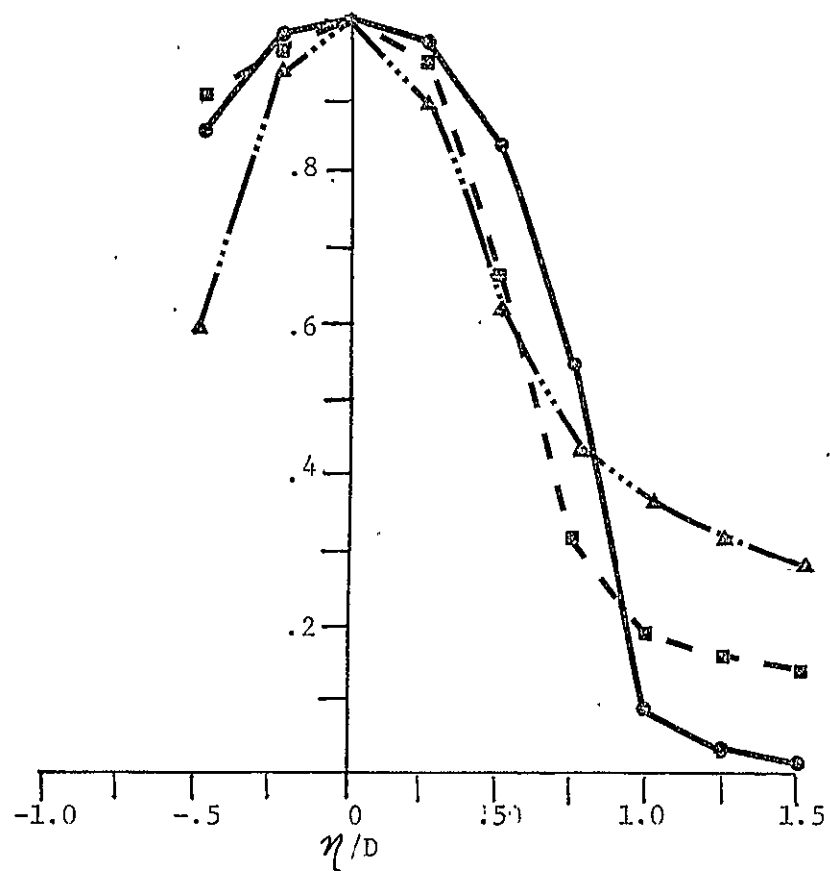


Figure 5.6.1 Jet Impingement Correlation Coefficients: $\beta=0^\circ$

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Probe Separation



Probe Separation

Figure 5.6.2 Jet Impingement Correlation Coefficients: $\beta=30^\circ$

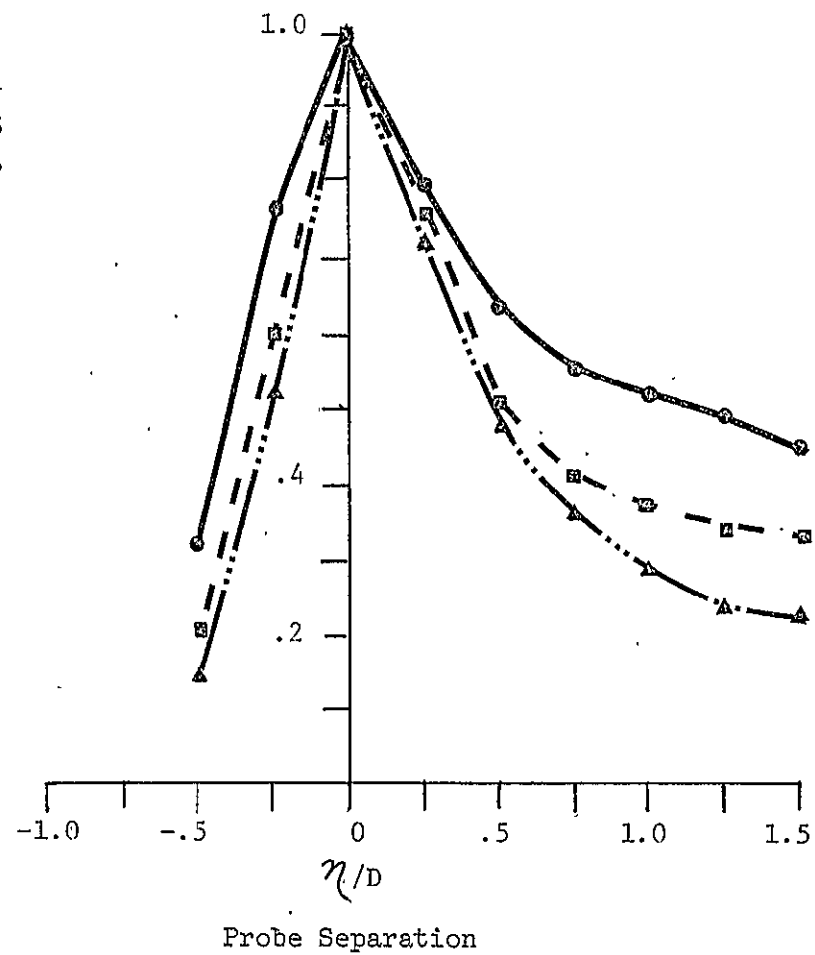
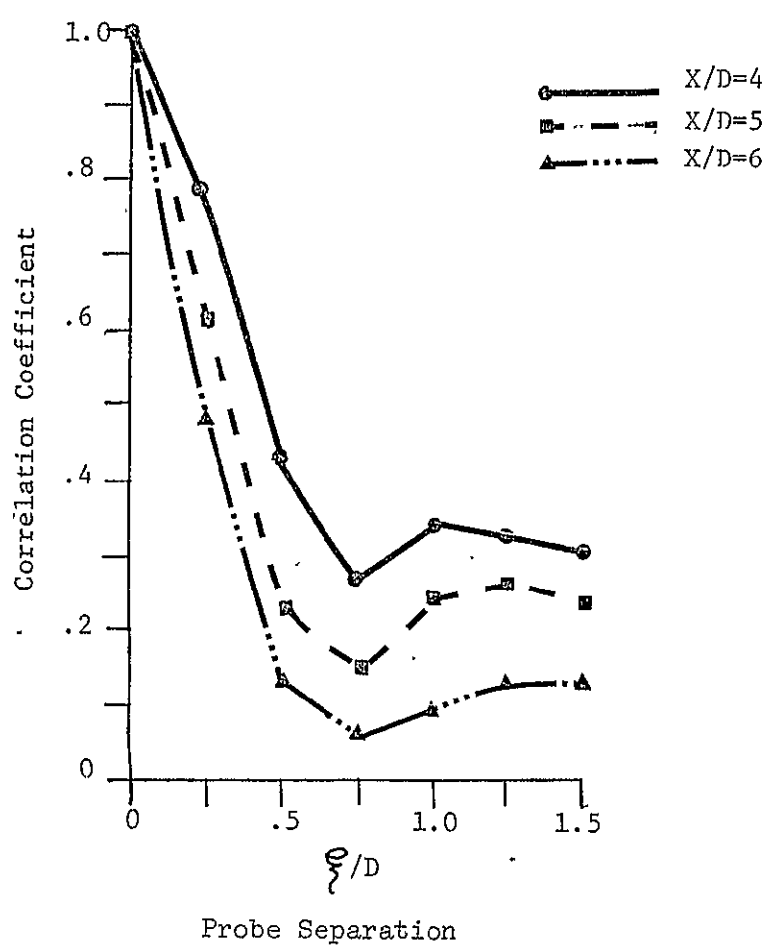


Figure 5.6.3 Jet Impingement Correlation Coefficients: $\beta=30^\circ$

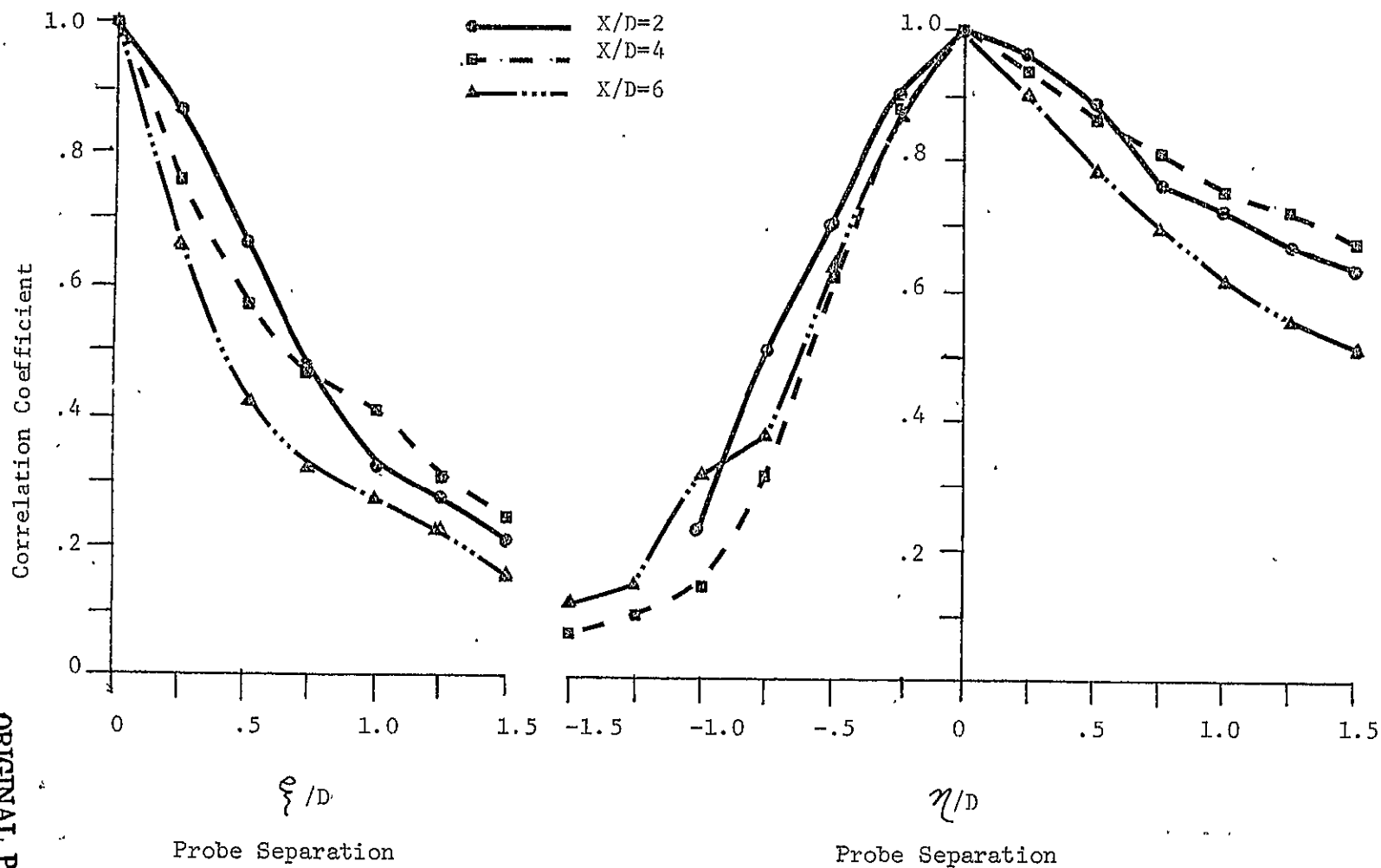


Figure 5.6.4 Jet Impingement Correlation Coefficients: $\beta = 60^\circ$

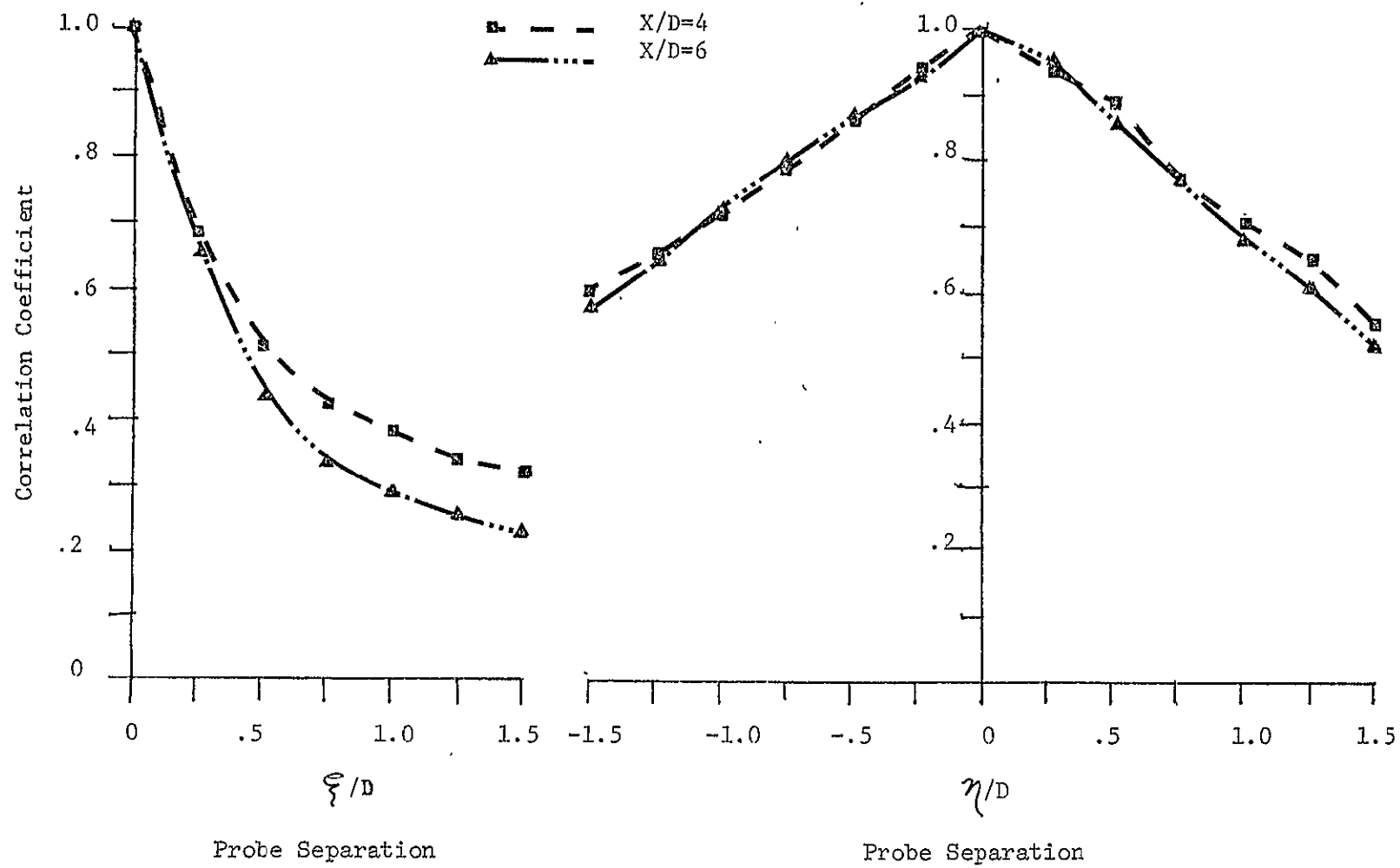


Figure 5.6.5 Jet Impingement Correlation Coefficients: $\beta=90^\circ$

with greatest correlation occurring up the plate in a relatively stream-wise direction.

5.7 Jet Impingement - Phase Lag, Transfer Function Amplitude and Coherence

Figures 5.7.1 - 5.7.19 show examples of the phase lag, transfer function amplitude and coherences on a flat plate. Cross correlations were obtained from two pressure ports simultaneously, one port always at the plate center, while the other could be varied both radially and streamwise along the plate surface from this first pressure port. This information was then fed through CROSSPECT to obtain phase lags, transfer function amplitudes and coherences versus Strouhal number.

The illustrated examples are for plate locations of 2, 4, and 6 diameters downstream with impingement angles of 0° , 30° , 60° , and the special case of grazing impingement (90°). The examples are for ports located 1 diameter apart in the upstream, downstream, and radial directions along the plate. [With exceptions at 30° impingement angle 2 diameters downstream].

The coherence curves in all the cases of 0° , 30° , and 60° angular orientation still indicate a dominant frequency (St. No. = 0.3) as was the case for the free jet. The dominance of this peak coherence decreases with increased downstream plate location. In the case of grazing impingement, the coherence is high throughout the frequency range, indicating highly correlated pressure disturbances.

The transfer function amplitude curves show how the spectral frequency contents vary between the two positions examined. At small impingement angles and plate locations near the exit of the jet, the influence of the secondary peak is quite apparent through the large dip

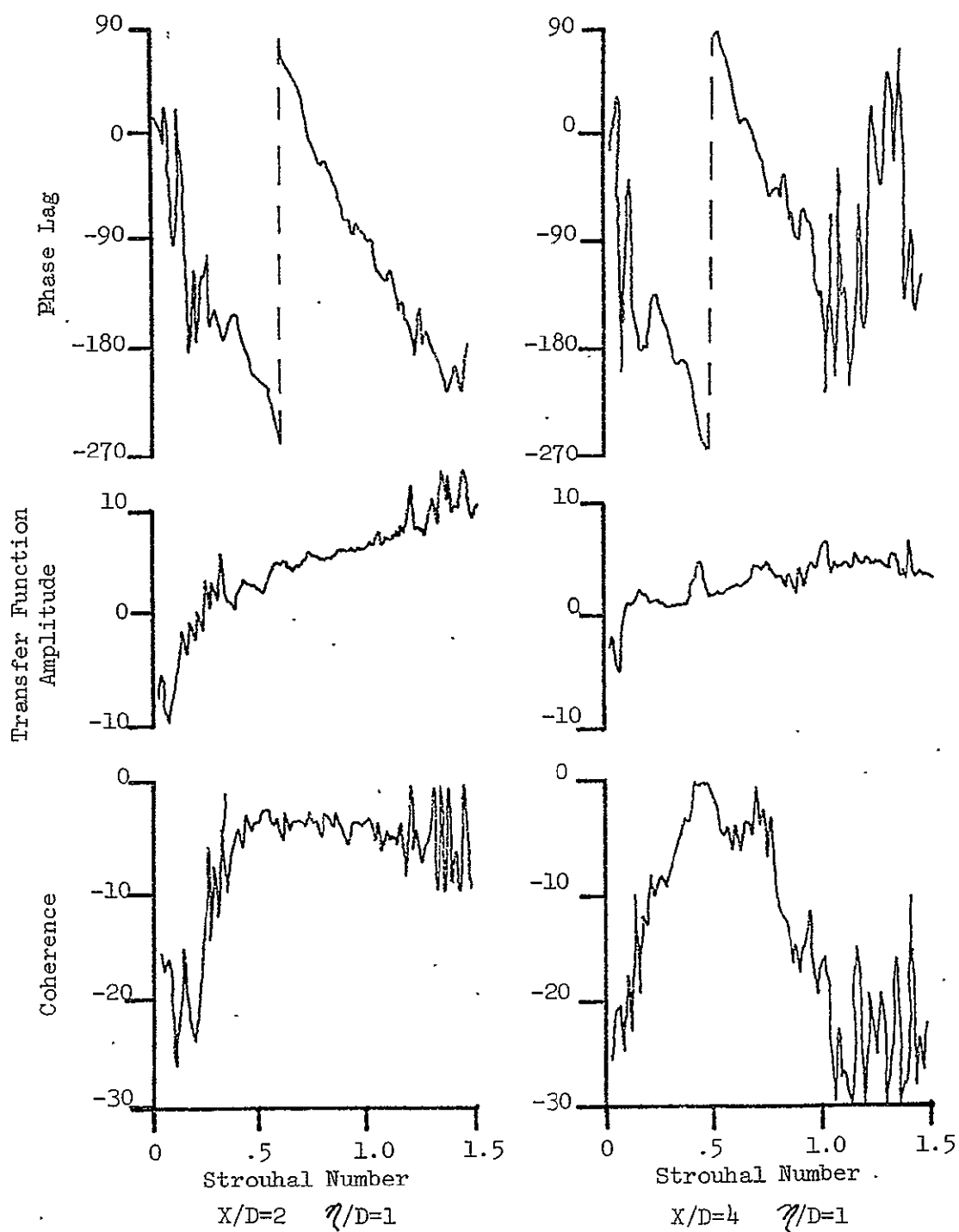


Figure 5.7.1 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta=0^\circ$; $X/D=2$ and 4 ; $\eta/D=1$

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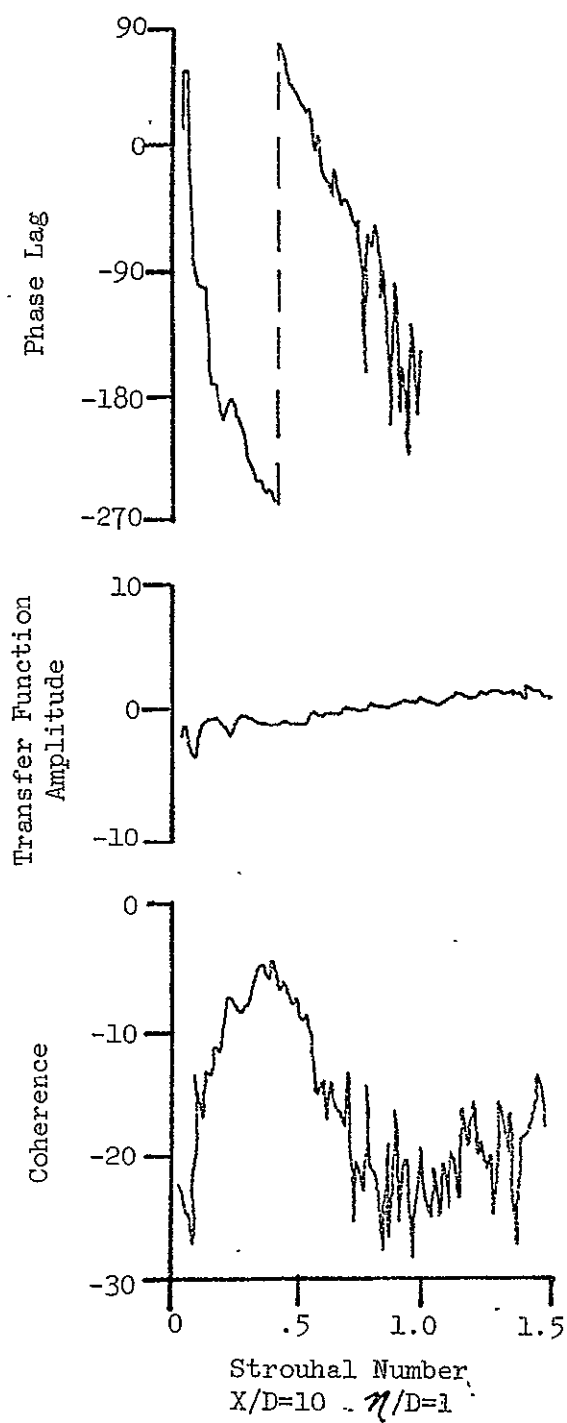


Figure 5.7.2 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta=0^\circ$; $X/D=10$; $\eta/D=1$

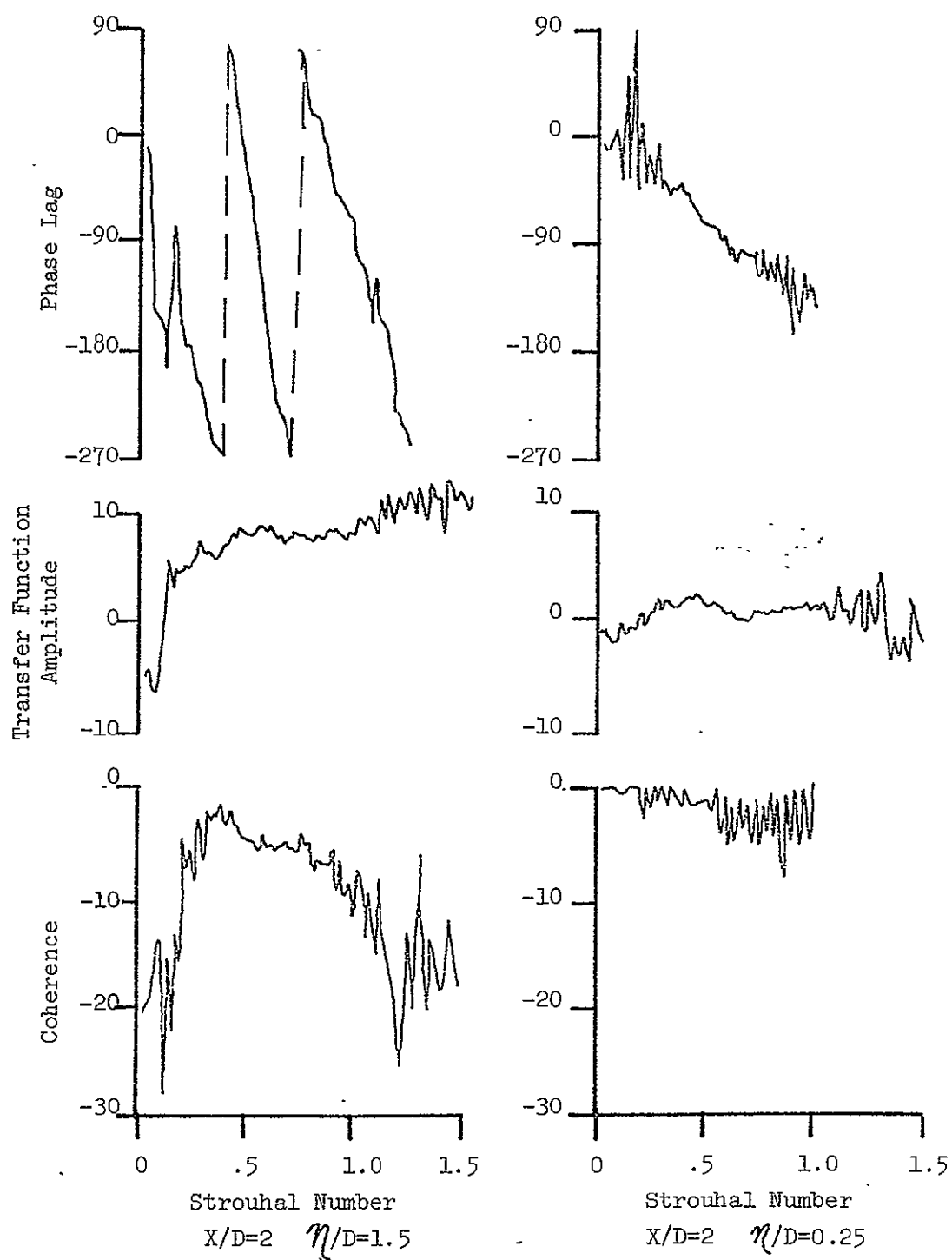


Figure 5.7.3 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 30^\circ$; $X/D = 2$; $\eta/D = 1.5$ and 0.25

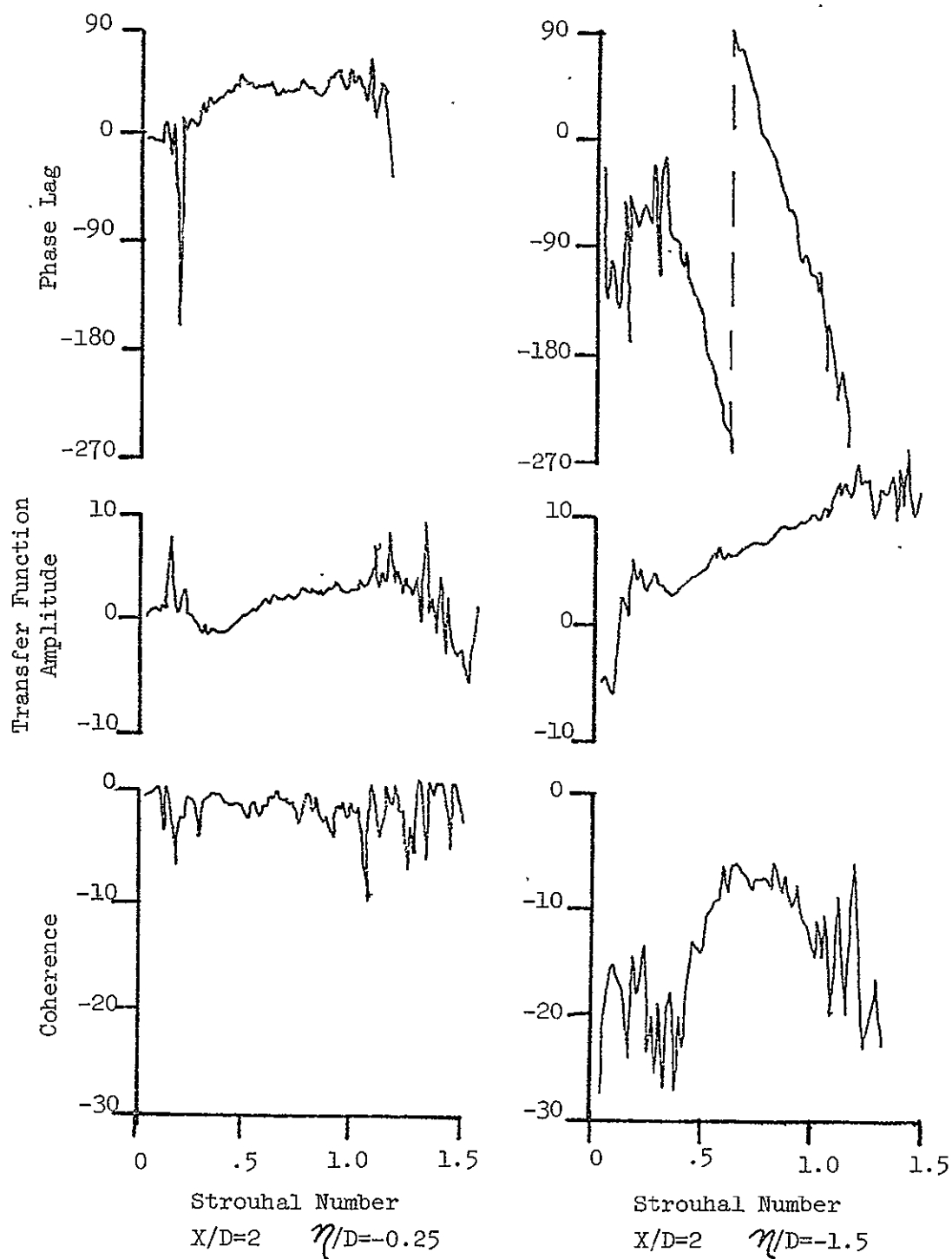


Figure 5.7.4 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta=30^\circ$; $X/D=2$; $\eta/D=-0.25$ and -1.5

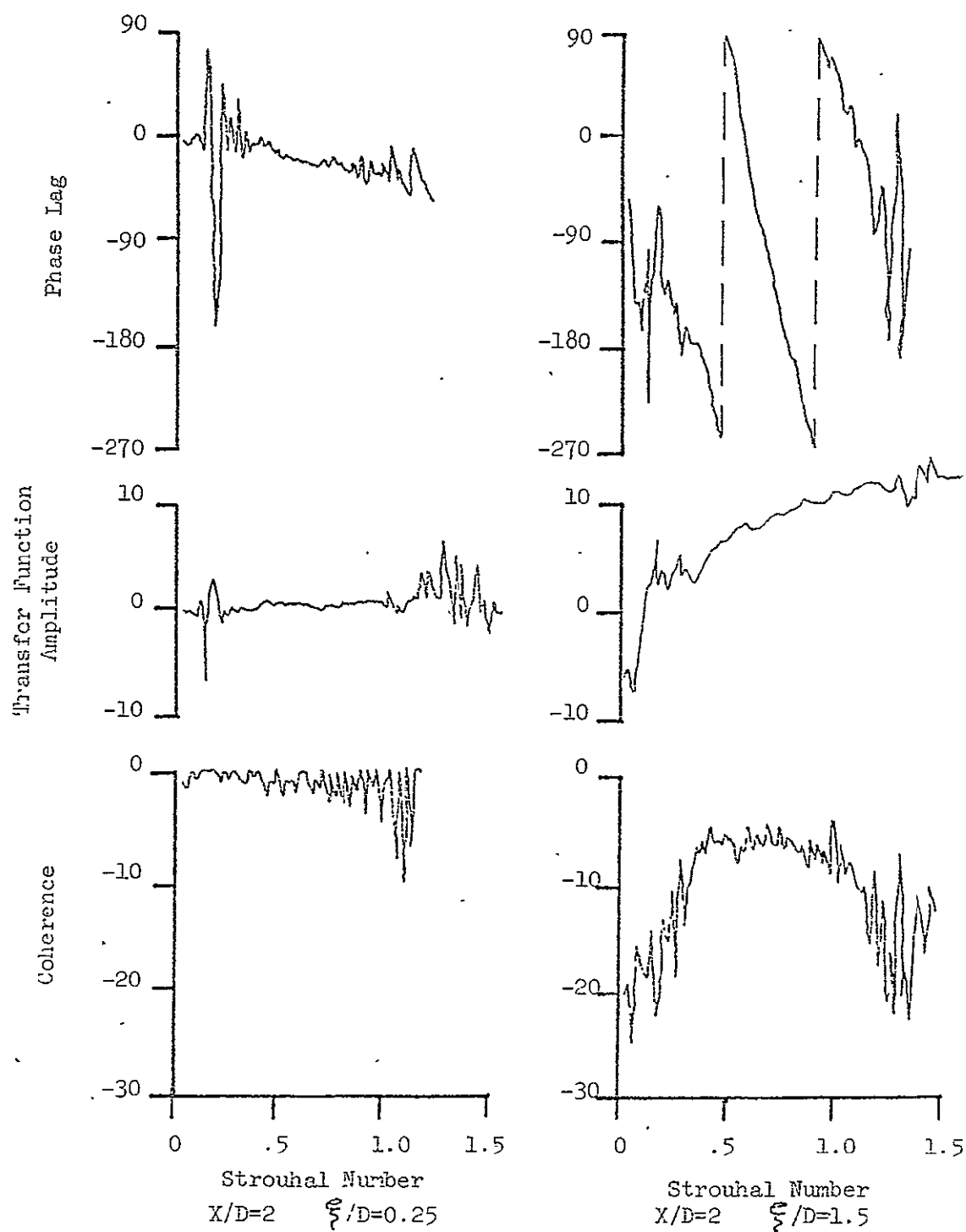


Figure 5.7.5 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 30^\circ$; $X/D = 2$; $\xi/D = 0.25$ and 1.5

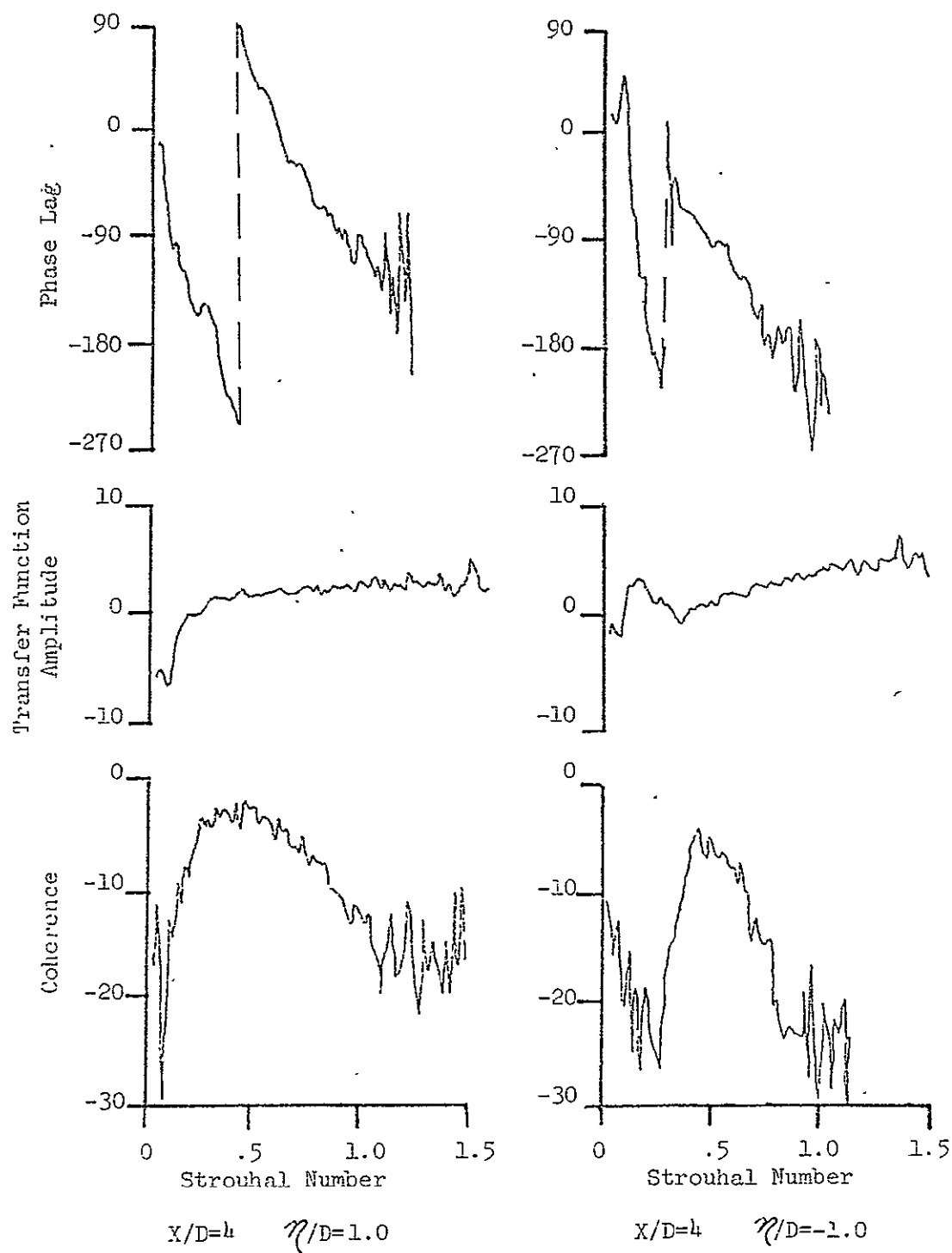


Figure 5.7.6 Jet Impingement phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta=30^\circ$; $X/D=4$; $\eta/D=1.0$ and -1.0

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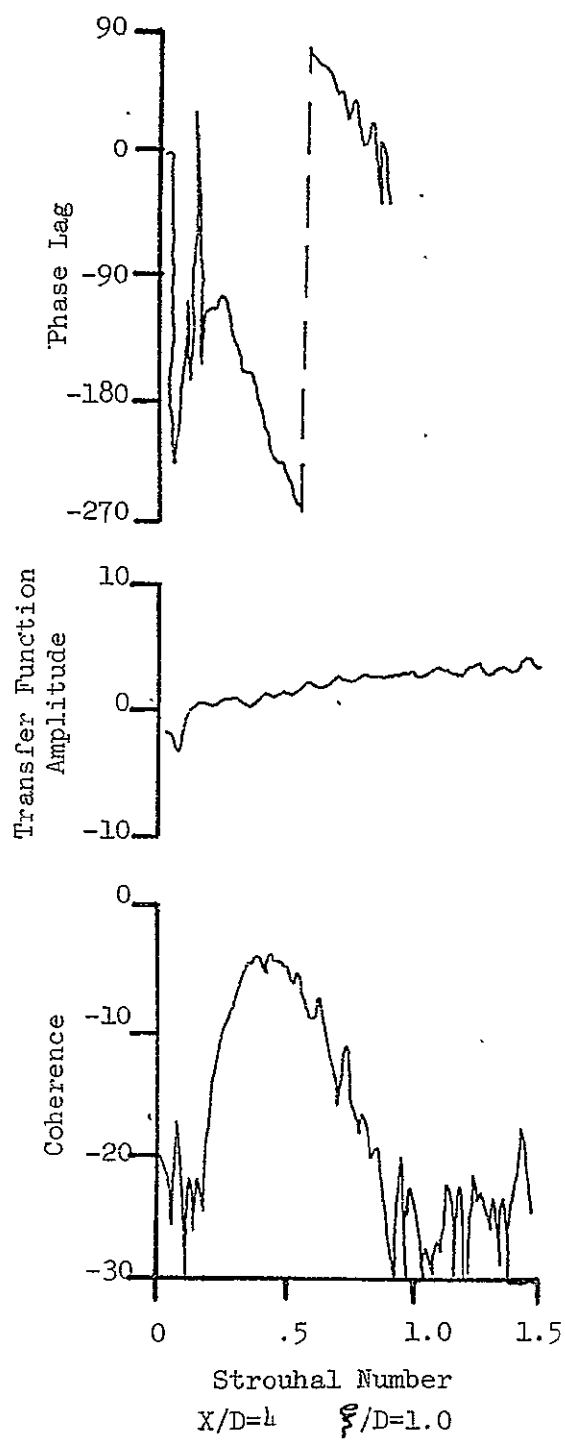


Figure 5.7.7 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 30^\circ$; $X/D=4$; $\xi/D=1.0$.

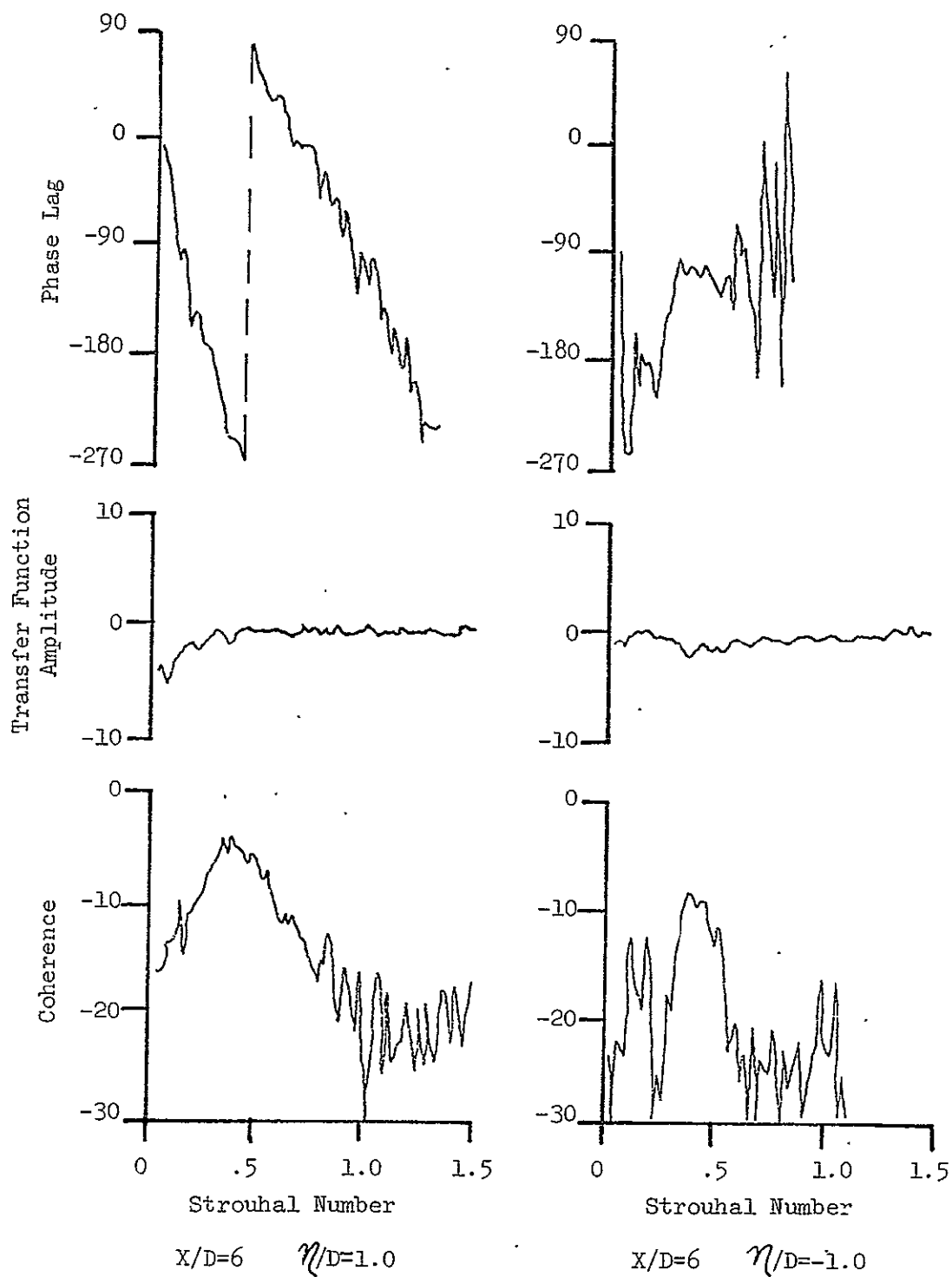


Figure 5.1.8 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta=30^\circ$; $X/D=6$; $\eta/D=1.0$ and -1.0

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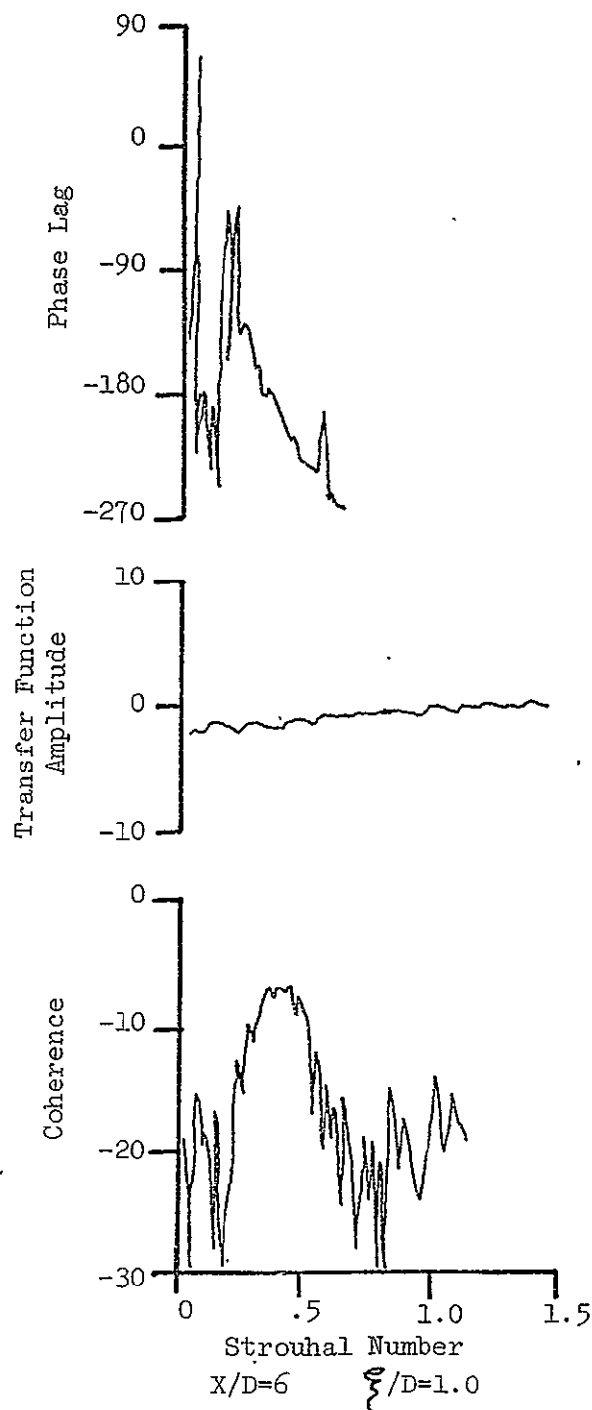


Figure 5.7.9 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 30^\circ$; $X/D=6$; $\xi/D=1.0$

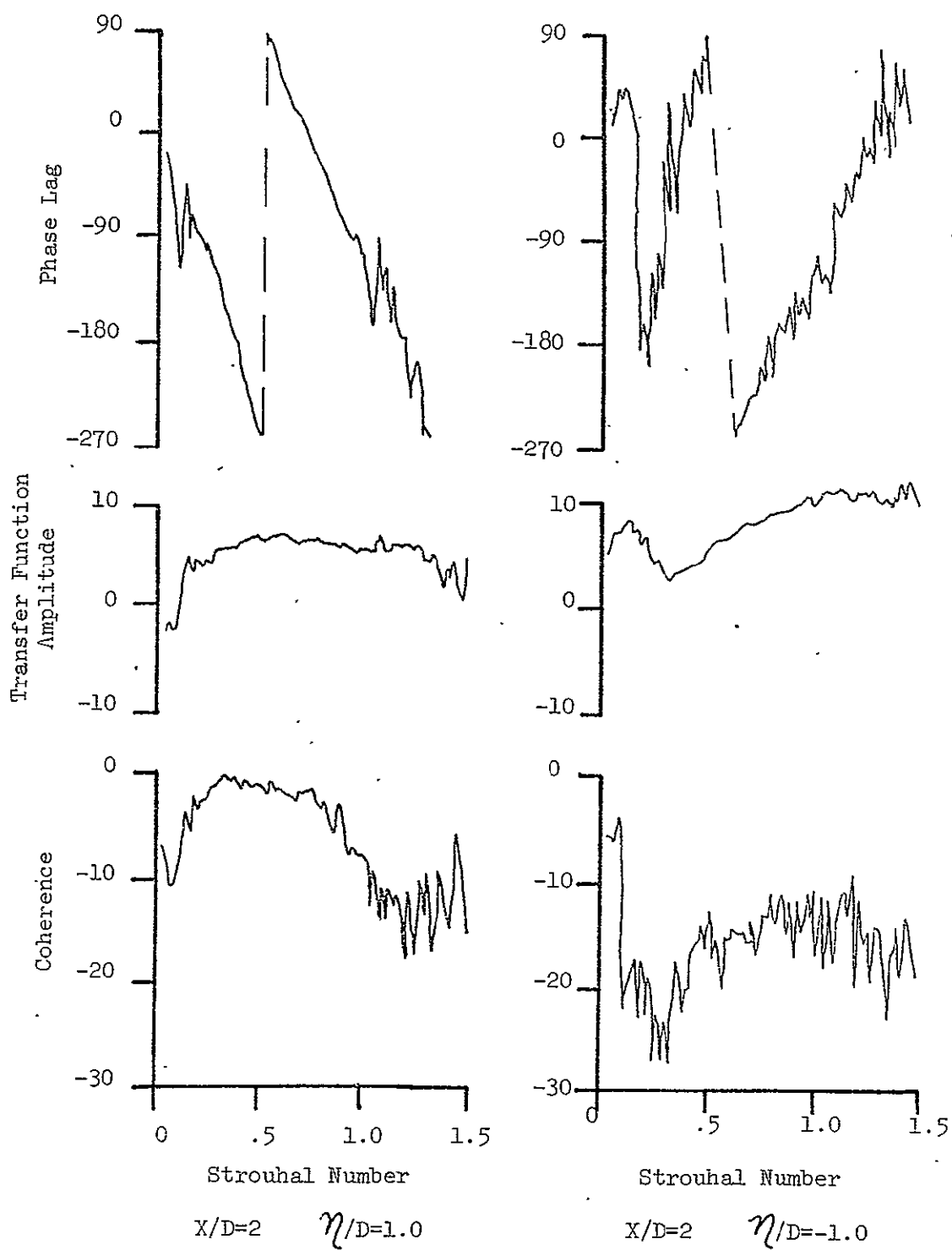
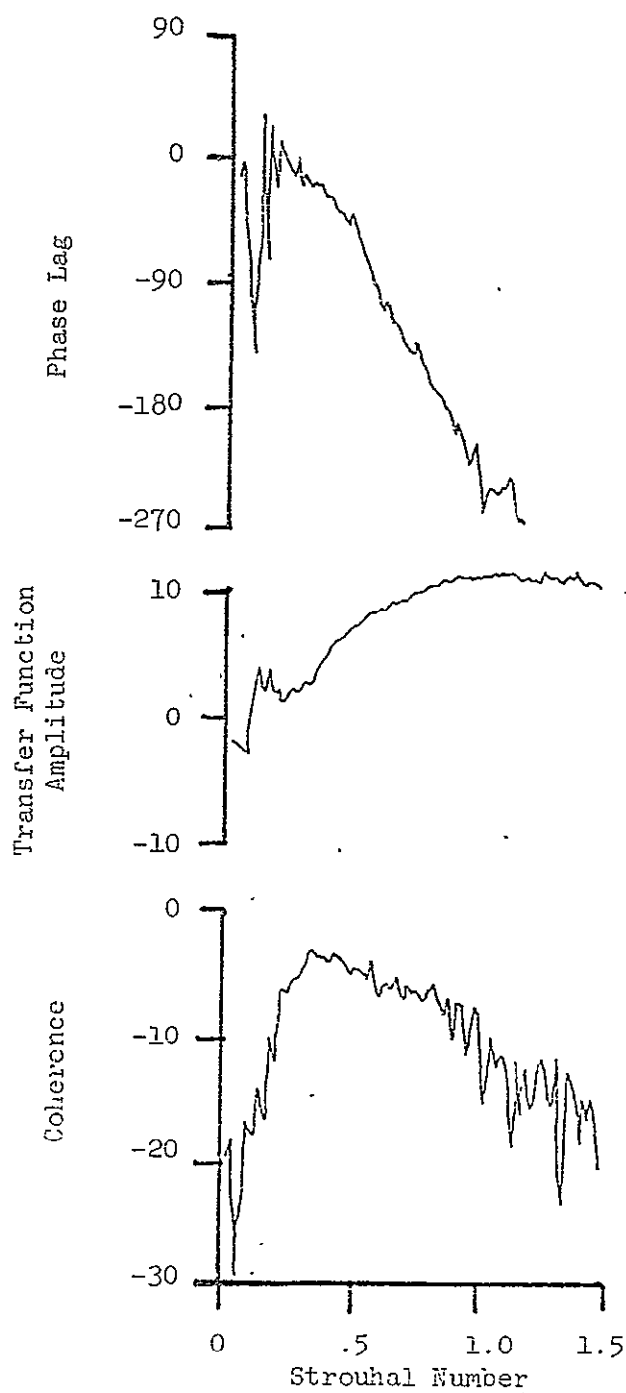


Figure 5.7.10 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta=60^\circ$; $X/D=2$; $\eta/D=1.0$ and -1.0

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$X/D=2$ $\xi/D=1.0$

Figure 5.7.11 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta=60^\circ$; $X/D=2$; $\xi/D=1.0$

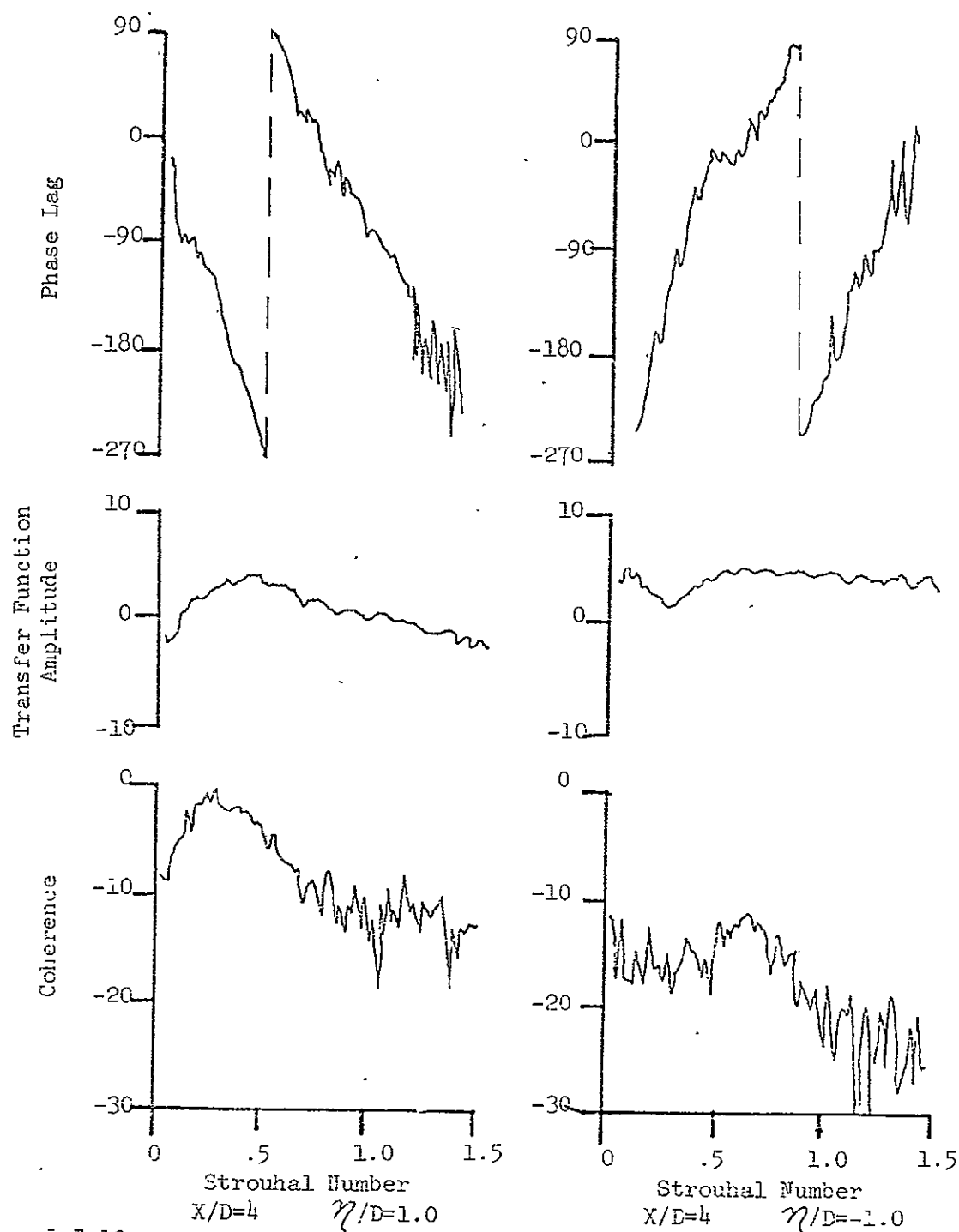


Figure 5.7.12 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 60^\circ$; $X/D = 4$; $\eta/D = 1.0$ and -1.0

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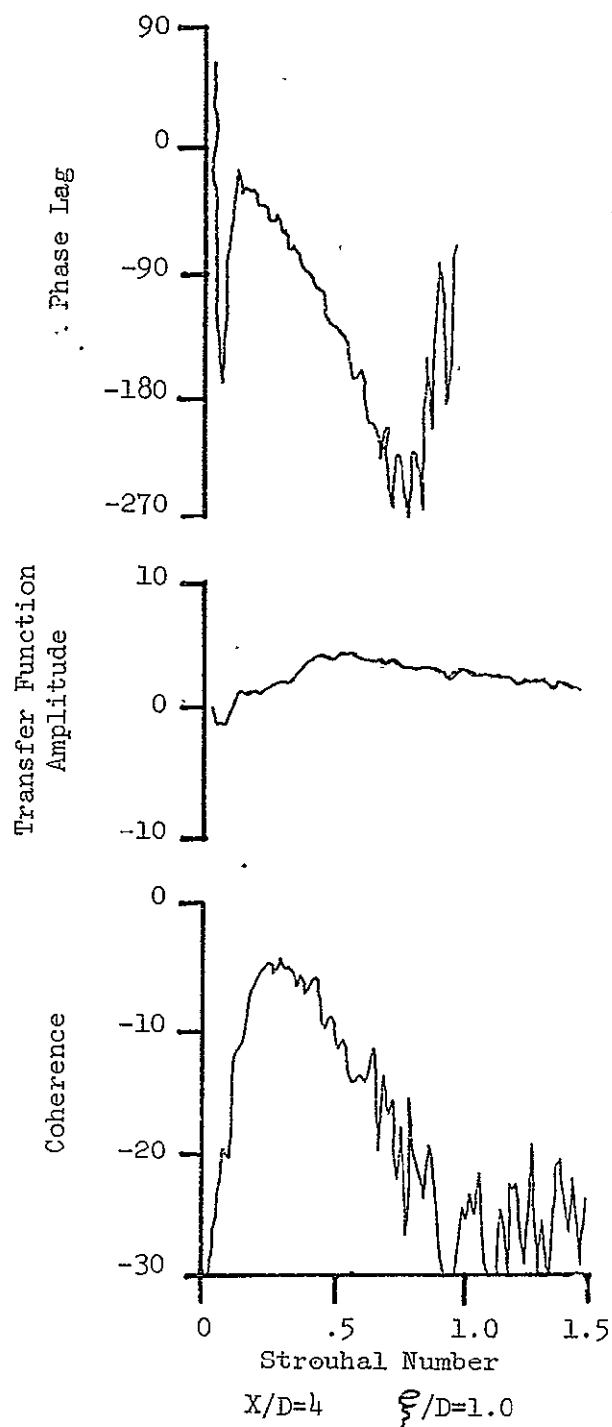


Figure 5.7.13 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 60^\circ$; $X/D=4$; $\xi/D=1.0$

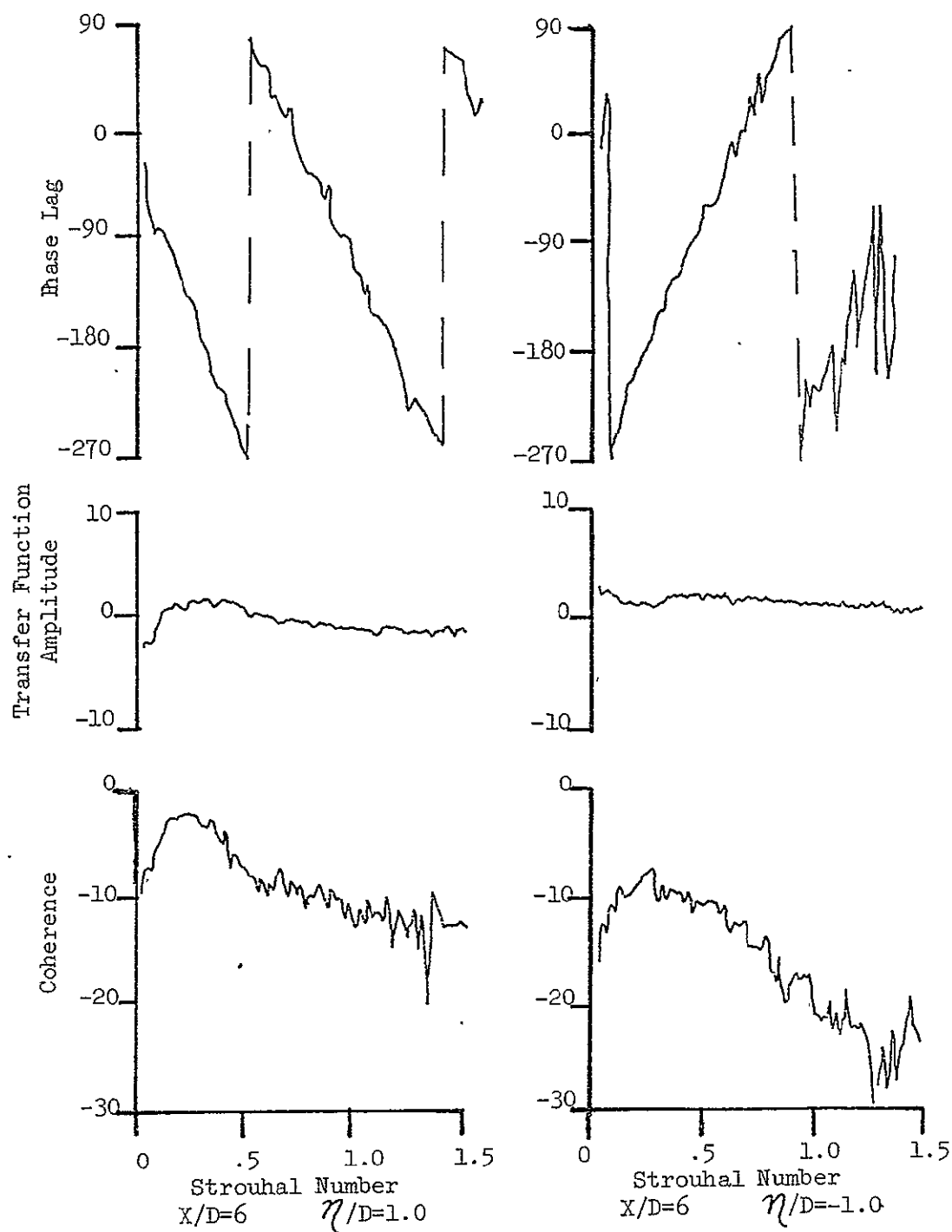


Figure 5.7.14 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 60^\circ$; $X/D = 6$; $\eta/D = 1.0$ and -1.0

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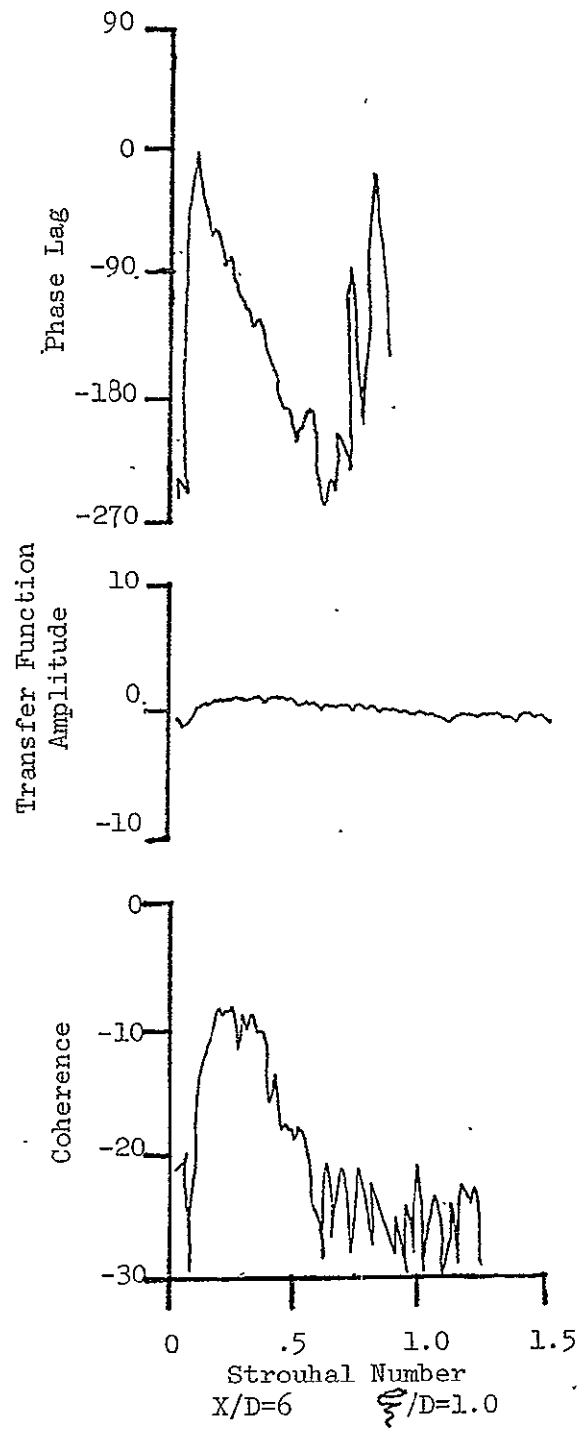


Figure 5.7.15 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 60^\circ$; $X/D=6$; $\xi/D=1.0$

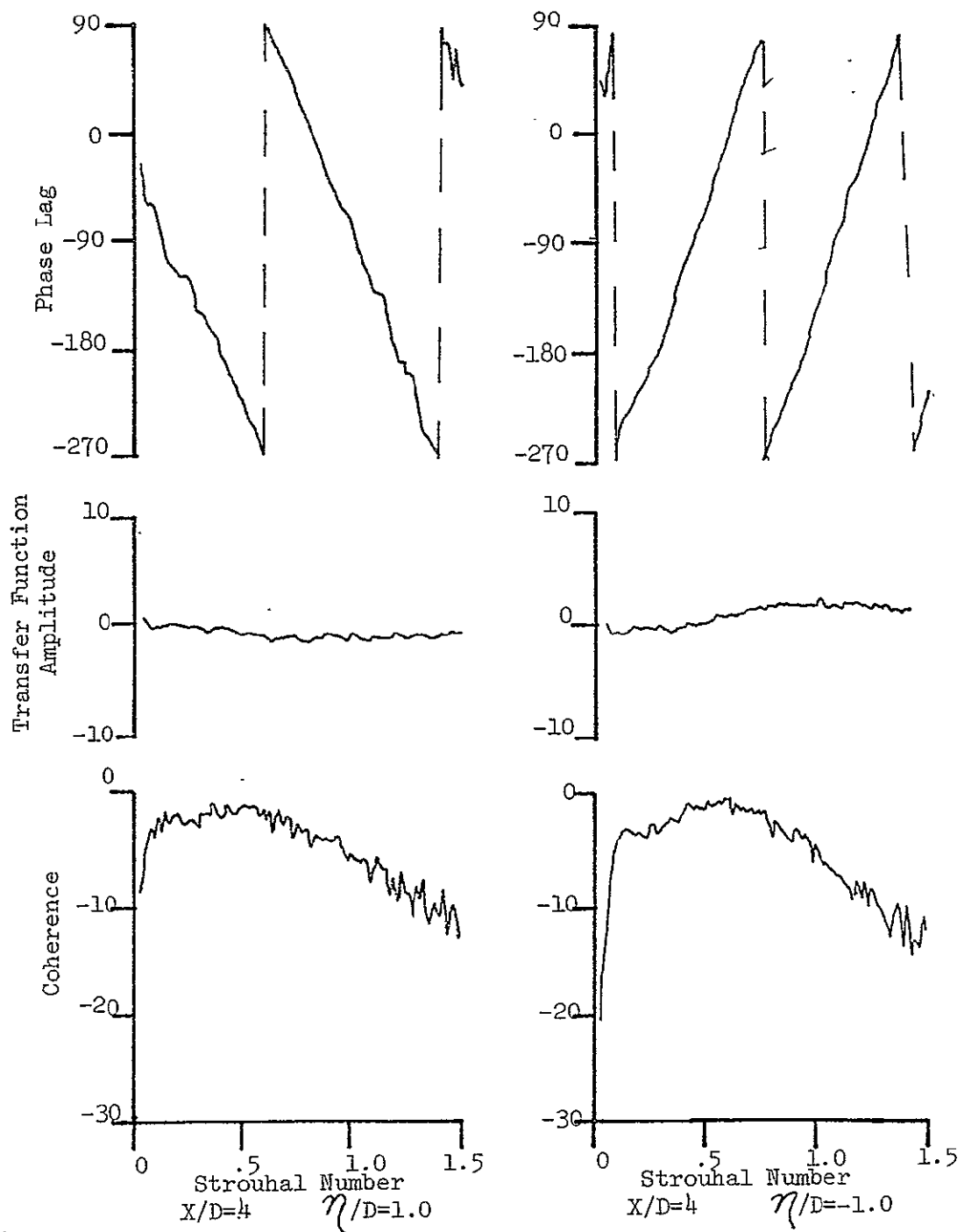


Figure 5.7.16 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 90^\circ$; $X/D = 4$; $\eta/D = 1.0$ and -1.0

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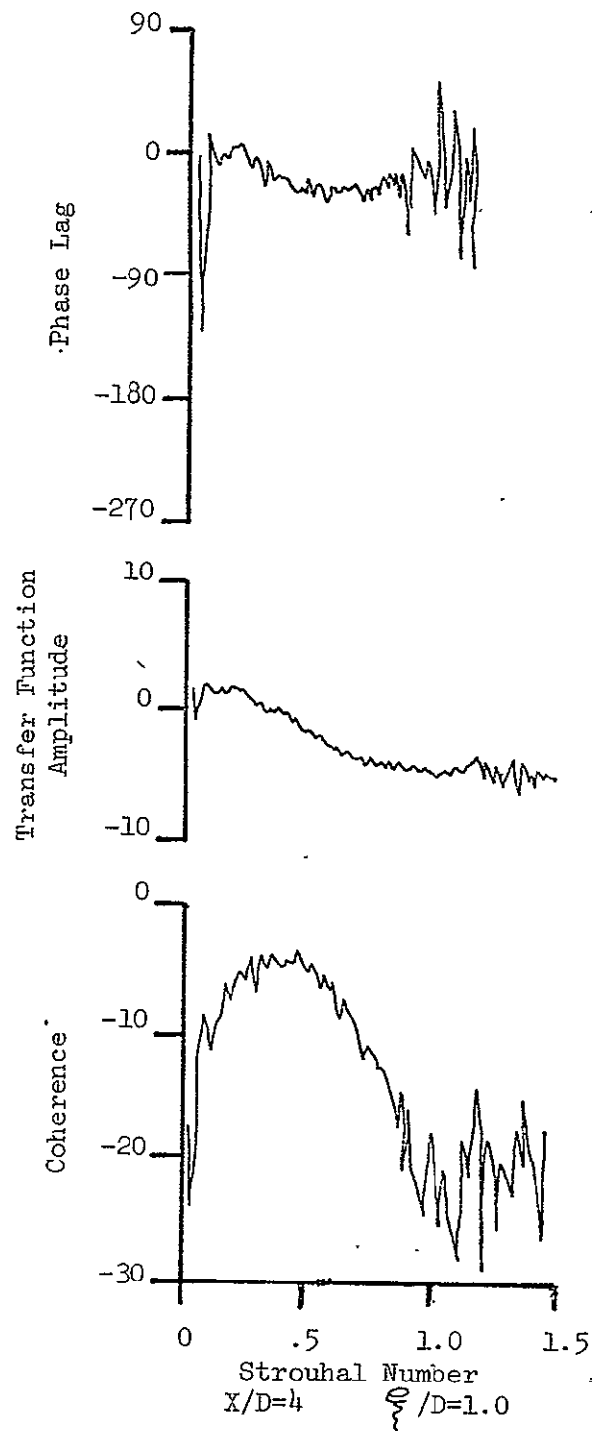


Figure 5.7.17 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 90^\circ$; $X/D = 4$; $\xi/D = 1.0$

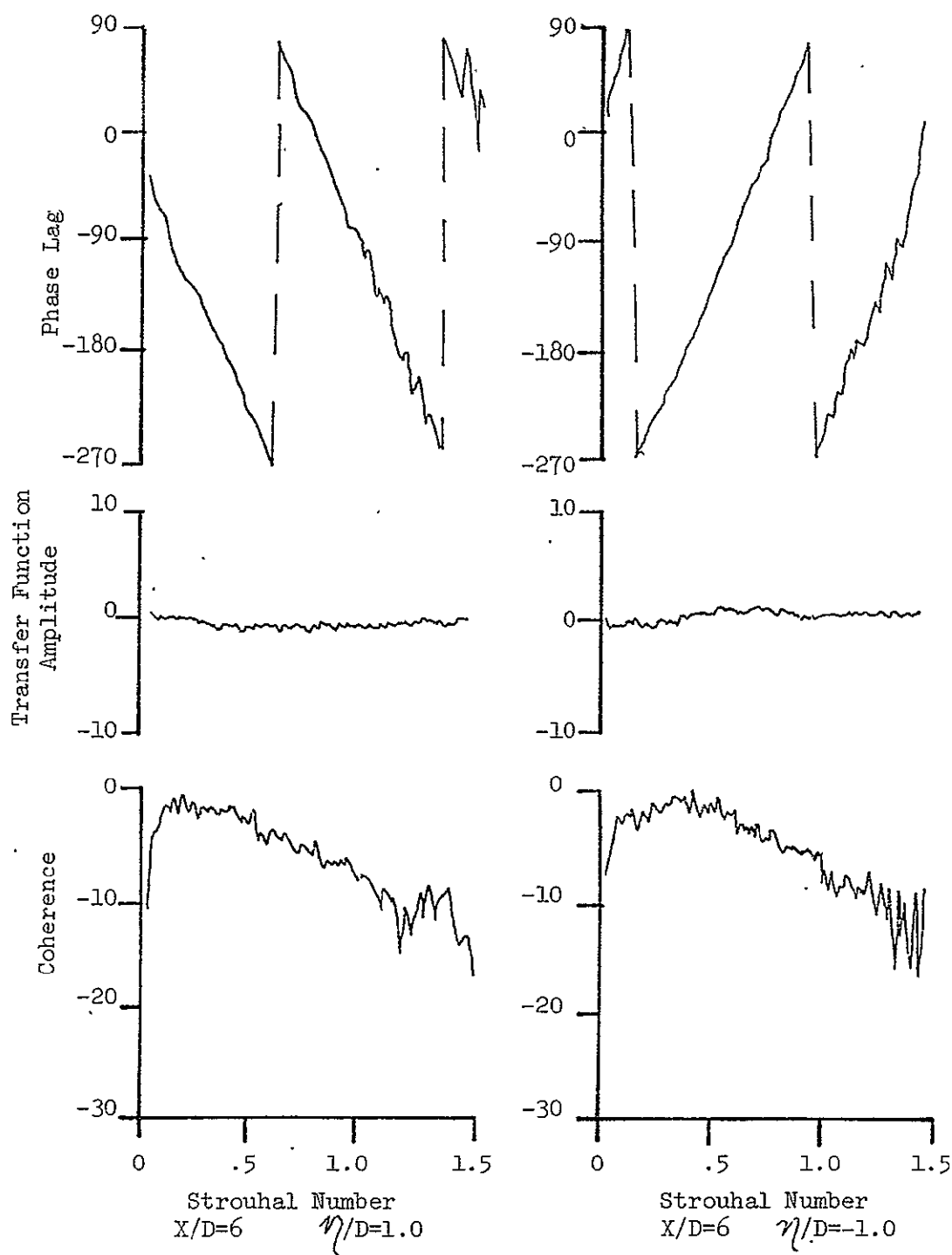


Figure 5.7.18 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta = 90^\circ$; $X/D = 6$; $\eta/D = 1.0$ and -1.0

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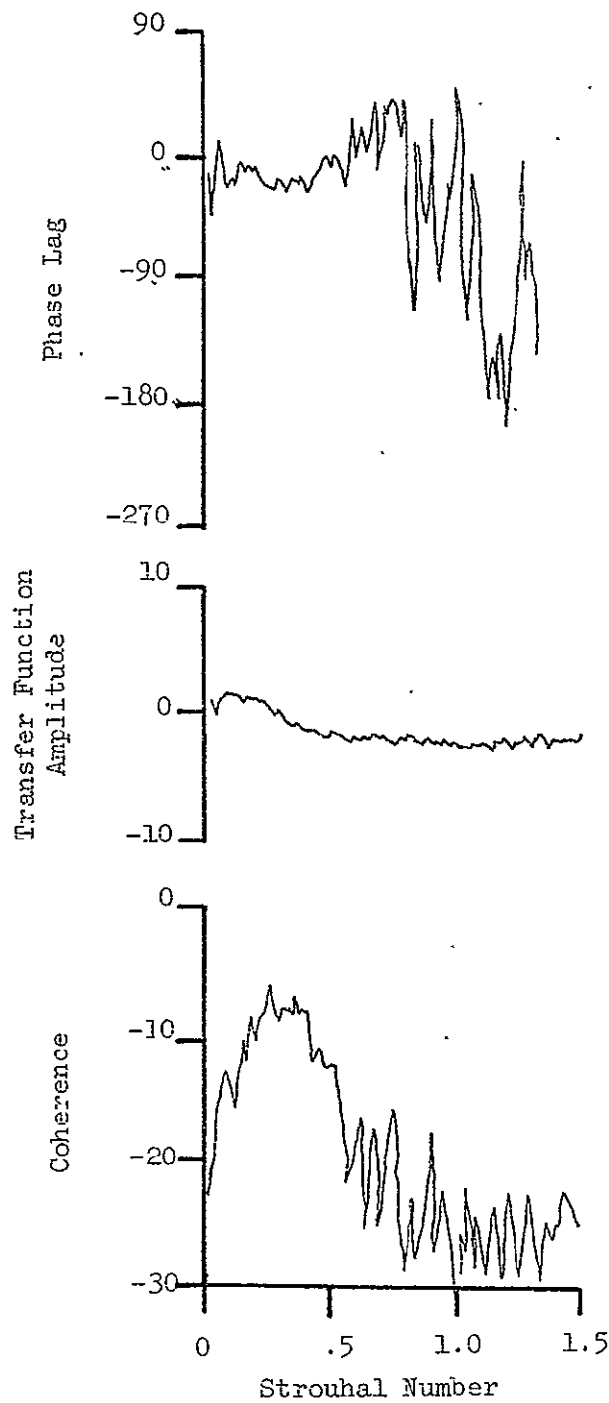


Figure 5.7.19 Jet Impingement Phase Lag, Transfer Function Amplitude and Coherence versus Strouhal Number
 $\beta=90^\circ$; $X/D=6$; $\xi/D=1.0$

in the curves at low Strouhal number values.

The phase lag curves indicate convection velocities that are tabulated in table 3 (positive convection velocity corresponds to disturbances that convect from the center of the plate to the variable probe). The convection velocities were found to vary from .6 to .9 times the jet exit velocity, corresponding to the induced flow along the plate. These values agree with convection velocities found in full scale tests. It is apparent that the reliability of these calculations are dependent upon the impingement angle. The secondary peak is the cause for these problems for all comparisons are made relative to the center of the plate. The trends of these convection velocities show that at small impingement angles the flow becomes extremely complex upstream of the centerpoint of the plate. This region encounters both flows convecting down the plate after being turned and also flow convecting up the plate after direct jet impingement. When the impingement angle is increased the vortex type disturbances seem to dominate and progress up the plate thus causing convections towards the plate centerpoint [negative convection velocity].

Table 3

Jet Impingement - Convection Velocities

β	X/D	η/D	ξ/D	U_c/U_j
0°	2	1.0	-	.8
0°	4	1.0	-	.7
0°	10	1.0	-	.5
30°	2	1.5	-	.9
30°	2	.25	-	.3
30°	2	-.25	-	-
30°	2	-1.5	-	-
30°	2	-	.25	-
30°	2	-	1.5	-
30°	4	1.0	-	.6
30°	4	-1.0	-	-
30°	4	-	1.0	.9
30°	6	1.0	-	.5
30°	6	-1.0	-	-
30°	6	-	1.0	.9
60°	2	1.0	-	.8
60°	2	-1.0	-	.4
60°	2	-	1.0	1.0
60°	4	1.0	-	.8
60°	4	-1.0	-	-.8
60°	4	-	1.0	1.0
60°	6	1.0	-	.8
60°	6	-1.0	-	-.9
60°	6	-	1.0	.9
90°	4	1.0	-	.8
90°	4	-1.0	-	-.8
90°	4	-	1.0	8
90°	6	1.0	-	.8
90°	6	-1.0	-	-.8
90°	6	-	1.0	8

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Chapter 6

SUMMARY

An experimental investigation of the near field fluctuating pressure behavior behind a cold free round jet and this jet impinging on a flat plate was made. The vortex model of a free jet was assumed and was further verified in this study.

It was also found that the jet diameter, velocity and dynamic pressure are appropriate scaling dimensions for characterizing fluctuating pressures behind the jet.

An experimental technique was developed to use specially designed pressure sensitive probes to investigate these different flow fields. Cross-correlation techniques were developed and used extensively to obtain quantities such as correlation coefficients, phase lags, transfer function amplitudes and coherences. Evaluation of the various probe systems were made and internal transfer functions were investigated.

The techniques and instrumentation developed was found to be reliable and capable of extracting the desired fluctuating pressure behavior. The theoretical transfer functions evaluated for the pressure sensing probe systems was found to be close to the transfer functions determined experimentally, however, there still is a need for refinement of these calculations. The majority of the presented results were obtained using identical pressure sensing systems, thus, cancelling the effect of these internal transfer functions for measured values of coherence, phase lag and transfer function amplitude.

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A short summary of some of the results obtained behind the free jet and the jet impinging on a flat plate follow:

1. The P_{rms} pressure profiles for the free jet indicate the highest levels occur behind the lip of the jet with lowest levels in the potential core region. Eventually these profiles approach a normal type distribution further downstream.
2. Mean dynamic pressure for the free jet remains fairly constant in the potential core region. The centerline pressures decrease as the jet spreads further downstream.
3. The 1/3 octave spectra behind the free jet show a spectral peak at Strouhal number of 0.3 to 0.4. This peak is associated with vortex ring passage as indicated by the vortex model of a free jet.
4. Correlation coefficients are very high in the initial zone of the free jet due to the dependence on the vortex passage.
5. Coherences behind the free jet are found to be very high at $St. No. = 0.4$, associated again with the vortex passage, verifying the vortex model. Phase lag information indicated that these pressure disturbances are convecting at .6 - .9 times the velocity of the jet.
6. The fluctuating pressure levels for the cases of jet impingement indicates that the presence of the potential core, noted by low fluctuating pressure levels, is still experienced close to the jet exit. The overall pressure levels tend to decrease with increasing impingement angle and increased down-

stream location. The area of highest fluctuating pressure levels is located upstream from the plate centerpoint. The overall fluctuating surface pressure levels on the plate were found to be higher than the static levels in the free jet.

7. The 1/3 octave spectra on the flat plate display the same basic phenomena as the free jet, with Strouhal peaks at roughly 0.3, except that the levels are much higher. Also a secondary peak is found at a lower Strouhal number, that as yet is not fully understood.
8. Correlation coefficients on a flat plate are relatively high, decreasing with decreasing impingement angle. The coefficients are lowest for upstream separations and seem to indicate that the pressure disturbances are generally propagating up the plate in the streamwise direction.
9. Coherence, phase lag and transfer function amplitude relationships on the flat plate indicate that the presence of the vortex type structure is still felt. However, at small impingement angles, the presence of the secondary peak does tend to confuse the available information. The convection velocities were again found to vary between .6 - .9, times the jet exit velocity. The direction of the convection was found to be outwards from the center of the plate with upstream component that becomes more dominant with increased impingement angle.

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